IGBP Report No. 35 and HDP Report No. 7
Land-Use and Land-Cover Change Science/Research Plan

Contents

Executive Summary

Land-use and land-cover change is significant to a range of themes and issues central to the study of global environmental change. The alterations it effects in the surface of the earth hold major implications for sustainable development and livelihood systems and also contribute to changes in the biogeochemical cycles of the earth, affecting the atmospheric levels of greenhouse and other trace gases. Understanding the nature of land-use/cover change and its impacts requires the joint efforts of natural and social science because of the expertise of each in certain key facets of the topic.

The global environmental change community has increasingly recognised the significance of land-use and land-cover change and the need for an interdisciplinary research approach to the subject. This recognition prompted the International Geosphere-Biosphere Programme (IGBP) and the Human Dimensions of Global Environmental Change Programme (HDP) to explore the possibility of a cooperative research project/programme with the general goal of improving our basic under-standing of the dynamics of Land-Use and Land-Cover Change (LUCC) globally, with a focus on improving our ability to model and project such change. The two programmes commissioned a Core Project Planning Committee/Research Programme Planning Committee1) for Land-Use and Land-Cover Change (CPPC/RPPC LUCC) to create a science/research plan2) for a jointly sponsored LUCC core project/research programme.

This report constitutes the LUCC science/research plan as developed by the CPPC/RPPC in cooperation with a larger research community through several workshops and meetings. Section 1 introduces the subject and its linkages with other global change research programmes and projects. Section 2 outlines the CPPC/RPPC LUCC's mandate from the IGBP and HDP. Section 3 describes the LUCC problem and the main themes and issues involved in its study. Section 4 is an overview of the science/research plan, while Sections 5-7 detail the three main research foci, and Sections 8-9 are the two integrating activities of the plan.

The plan rests on the following observations:

1. That a truly international and interdisciplinary LUCC core project/research programme is possible 2. That a sufficiently large cadre of scientists and social scientists exists worldwide to undertake the effort now 3. That LUCC-related projects and programmes are emerging in various segments of the global change research community, many of them in anticipation, but independent, of an IGBP-HDP core project/research programme 4. That these various initiatives are, individually and in the aggregate, insufficient for the global nature of the problem, which requires the kind of integration and inter-disciplinary effort that an IGBP-HDP core project/research programme can provide. The plan is guided by five overarching questions, specifically: 1. How has land cover been changed by human use over the last 300 years? 2. What are the major human causes of land-use change in different geographical and historical contexts? 3. How will changes in land use affect land cover in the next 50-100 years? 4. How do immediate human and biophysical dynamics affect the sustainability of specific types of land uses? 5. How might changes in climate and global biogeochemistry affect both land use and land cover, and vice versa?

Because the study and analysis of research addressed by LUCC covers a new interdisciplinary area, and because it is recognised that considerable integration of LUCC research with that of other Core Projects will be necessary, these goals will only be met through close collaboration with other Core Projects.

The plan calls for a set of integrative research foci and activities linking the various components of the LUCC research community in an effort to improve understanding of: (i) the driving forces (exogenous variables) of land use as they operate through the land manager; (ii) the land-cover implications of land use; (iii) the spatial and temporal variability in land-use/cover dynamics; and (iv) regional and global models and projections of land-use/cover change.

These questions are addressed by three research foci:

Focus 1 Land-Use Dynamics, is a comparative case study approach aimed at improving our understanding of the variation in the nature-society dynamics of land management, thereby facilitating a sophisticated approach to regional and global modelling. It aims to identify and analyse a series of regional situations that represent the major clusters of LUCC dynamics worldwide, including the dynamic forces of these dynamics, thus permitting spatial and temporal fine-tuning of the overall modelling effort as well as providing the local, and, with Focus 2, regional understanding that is vital for climate impact and sustainability research.

Focus 2 Land-Cover Dynamics, involves regional assessments of land-cover change as determined from direct observation (e.g., satellite imagery and field studies) and models built from these observations. It seeks to provide spatial specificity in the land-cover outcomes associated with the management practices of particular land uses. In doing so, it links the underlying driving forces and land uses found in the case studies of Focus 1 to land-cover changes through management or proximate activities. It also extends and specifies the spatial coverage of particular LUCC dynamics, while providing models of change in this coverage.

Focus 3 Regional and Global Models, aims to improve upon existing models and build new ones that provide a basis for projecting land-use changes based on changes in the underlying causes or driving forces. These models will incorporate the regional and situational sensitivity provided from Foci 1 and 2 to generate more spatially explicit outcomes from regional and global models. Focus 3 will develop a model structure able to integrate a variety of approaches

while strengthening agricultural sector models by including water, urban, biophysical, and other such linkages, and coupling these models to forest/timber and livestock sector models.

Two integrating activities cross-cut these three research foci:

Integrating Activity 1 Data and Classification, analyses data availability and quality and devises a classification structure suitable for the various needs of the three research foci. It also identifies, and, if needed, develops the major datasets and measures important for LUCC studies.

Integrating Activity 2 Scalar Dynamics, recognises that the different scales at which LUCC processes operate, and the different scales at which they are analysed, pose major impediments to developing a comprehensive understanding of LUCC. This activity seeks to identify the major rules and lessons that should guide LUCC efforts in this regard, thus improving the integration of the three foci.

The LUCC research activities will contribute to the following needs of the global environmental change communities:

1. Methodological advancement in the design and implementation of LUCC case studies and case study protocols, the means to interpolate and extrapolate from LUCC sample data across space and time scales, and the structure and functioning of integrated LUCC models 2. Analytical advancement in a suite of integrated LUCC models ranging from the household and farm to the globe 3. In cooperation with other projects and programmes, LUCC data development and format design 4. Empirically-derived inventories of geographically specific land-use/cover changes and analytically-derived projections thereof across specific time scales.

The understanding gained from the results of a LUCC project/programme will be of use to a wide range of researchers, policy planners, and other decision makers requiring improved means of projecting land-use/cover change in terms of its implications for (i) global environmental change, (ii) local-to-regional sustainability issues, and (iii) the assessment of responses to local and environmental change.

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3. Scope and Main Subjects of LUCC

Land-Use/Land-Cover Dynamics and Linkages

The terrestrial or land covers of the earth and changes therein are central to a large number of the biophysical processes of global environmental change. *Land cover is the biophysical state of the earth's surface and immediate subsurface* (Fig. 3). Changes in land cover include changes in biotic diversity, actual and potential primary productivity, soil quality, and runoff and sedimentation rates (Steffen et al. 1992). Land covers and changes in them are sources and sinks for most of the material and energy flows that sustain the biosphere and geosphere, including trace gas emissions and the hydrological cycle (BAHC 1993; Holligan and de Boois 1993; Matson and Ojima 1990).

Because contemporary land cover is changed mostly by human use (Allen and Barnes 1985; Turner, Kasperson et al. 1990; Whitby 1992), an understanding of land-use change is essential to understanding land-cover change. *Land use involves both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation - the purpose for which the land is used.* Forestry, parks, livestock herding, suburbia, and farmlands are, for example, classes denoting intent or purpose. Biophysical manipulation, by contrast, refers to the specific way in which human uses treat vegetation, soil, and water for the purpose in question: for example, the cut-burn-hoe-weed sequence in many slash-and-burn agricultural systems; the use of fertilisers, pesticides, and irrigation for mechanised cultivation on arid lands; or the use of an introduced grass species for pasture and the sequence of movement of livestock in a ranching system. Biophysical manipulation can be seen as the techno-managerial system.

Land use affects land cover with various implications. The present understanding of use-cover relationships, however, is inadequate, impeding progress towards certain objectives of the global change community, such as the ability to project use-cover changes. To improve this understanding, land use and cover must be linked to human actions. These actions are the product of individual and group behaviours within specific socio-economic and environmental settings. These behaviours and settings are extremely complex, but can be grouped into common or typical patterns in broadly similar environments and political economies.

Land-use and land-cover change and global environmental change form a complex and interactive system linking human action to use/cover change to environmental feedbacks to their impacts and human responses. Further complicating this system is the fact that the linkages occur at different spatial and temporal scales. The outflow of soil nutrients, for example, has immediate impacts on land productivity, vegetation changes and soil erosion, mid-term impacts on landscape fragmentation and land productivity, and possible long-term impacts on climate change.

Figure 4 illustrates this system. Varied human driving forces (e.g., population or development), mediated by the socio-economic setting (e.g., market economy, resource institutions) and influenced by the existing environmental conditions or context, lead to an intended land use (e.g., livestock herding) of an existing land cover (e.g., forest) through the manipulation of the biophysical conditions of the land.

Elsewhere these manipulations (e.g., cutting and burning) have been referred to as proximate sources of change (to distinguish them from the underlying human forces of change) or the most immediate activities or actions that create change. These actions may convert the existing cover, in this case by cutting, burning and planting to create a grassland, or modify it through introducing new grasses into existing pastures. Either cover response is further affected by biophysical forces that change it unless human inputs are used to maintain the converted or modified cover (physical maintenance: e.g., fertilising and weeding). These land-cover changes act as sources or sinks of biogeochemical flows (e.g., greenhouse gases), the feedbacks from which may affect the use-cover relationship. These feedbacks, as well as the changes in the land, may themselves affect the driving forces and the social setting in which they operate, and these effects, of course, may alter the intended land use.

Examples of these kinds of dynamics have followed at least three research paths considering: land use and land cover as forcing functions of other global environ-mental changes, both currently and in the past, as well as other global changes, such as potential climate change, as forcing functions of land use and land cover (Melillo et al. 1993). The three paths, of course, cover much common ground, but the path chosen may influence the conclusions reached. The third path - environmental-change impacts on land use/cover - largely addresses the "what if " question through scenario building with the aim of projecting the use-cover consequences of certain levels and kinds of climate change (e.g., Emanuel, Shugart and Stevenson 1985; Houghton et al. 1990; Rosenzweig 1985; Parry, Carter, and Konijn 1988; Parry 1990; Cramer and Leemans 1993; Rosenzweig and Hillel 1993; Rosenzweig and Parry 1994). Emphasis is placed on modelling the scenarios, all of which are based on simplifying assumptions about human behaviour and decision making and their meaning for land-use change. The former two paths - the causes and consequences of land-use/cover change - largely aim toward understanding the social, political, and economic factors that influence land use, occasionally addressing environmental components of the problem, but rarely those directly relevant to most global change studies. A major exception is work drawing on remotely sensed imagery of land cover linked to land uses, proximate sources of change, and, to a lesser degree, the underlying human causes in order to improve knowledge of carbon flows and biodiversity change (e.g., Moran et al. 1994; Skole et al. 1994). As noted, however, land-use/cover change is not a recent phenomenon, and the "what was " path has produced considerable documentation of it for various regions and locales, particularly for the recent past (e.g., Crumley and Marquardt 1987; Foster 1992; 1993; Foster et al. 1992). This information and interpretations generated in the path offer lessons with which to frame land-use/cover dynamics, particularly for transitory stages of change, and provide a factual basis on which to test models by "backcasting " them.

The programme of study proposed here seeks to join the research following all three paths. Its primary aim is to improve our understanding of current and future land-use/cover dynamics in order to model land-use/cover change (what is). To do so, however, requires an understanding of these dynamics at various times in the past (what was). Achieving this understanding is essential to the "what if " path to improving projections and scenario building (Meyer and Turner 1994; Turner, Meyer and Skole 1994; Turner, Moss and Skole 1993). In addition, the central path we have chosen is the one least developed within global change research.

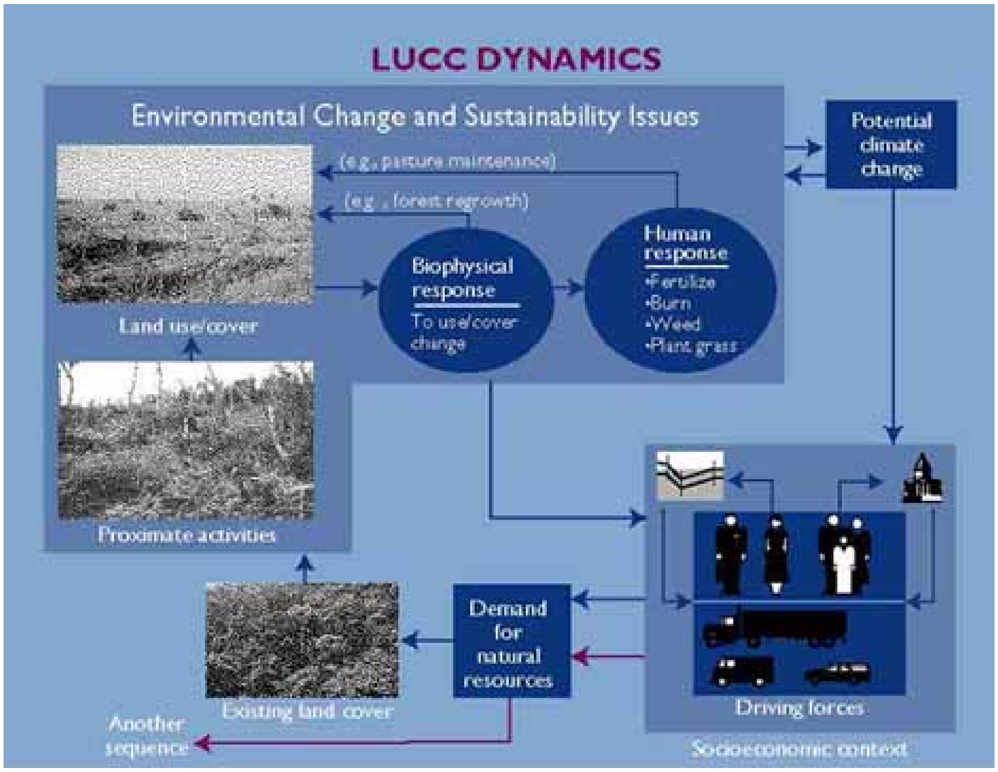

Figure 4. LUCC Dynamics.

Land-Cover Conversion and its Environmental Impacts

Humankind has altered terrestrial ecosystems since, at least, the use of fire to hunt and the advent of plant and animal domestication (Thomas 1956). Such change increased dramatically throughout the agricultural phase of history (Wolman and Fournier 1987), most strikingly in deforestation (Williams 1990a) and the transoceanic movement of species (Crosby 1986; Turner, G—mez Sal and di Castri 1994). These changes were of no small consequence, and yet in spatial scale, magnitude, and pace they pale in comparison to those produced by modern industrial society. Today, land-cover changes of many kinds are global in spatial scale and magnitude and rapid, if variable, in pace, some of them large enough to contribute significantly to changes in global biogeochemical flows.

A significant amount of literature documents and interprets the character of modern land-use/cover change. It is too vast to be fully treated here; the several examples provided below must suffice (for a review, see Meyer and Turner 1992).

Impacts on Land Covers (States/Faces)

From 1700 to the mid-1980s, the largest land-cover change involved cropland, which increased globally by 392% to 466%, depending on the means of estimation, or from an area roughly the size of Argentina to that of the South American continent (Richards 1990). It grew at the expense of forest, grassland, and wetlands. Change accelerated globally, in terms of both the conversion of lands to cultivation and the intensification of agriculture on land already cultivated. The net global area of irrigated cropland increased by 2,400% over the last 200 years, from 80,000 km2 to 2,000,000 km2 (Richards 1990). Today, cropland conversion and, perhaps, intensification are most rapid in the less industrialised portions of the world, while the area of cropland has decreased in Europe (Richards 1990). Since pre-agricultural times, worldwide forest/woodland/tree cover has diminished by about 15% (Williams 1990a), although this figure could change considerably with changes in the definition of what is counted as forest or woodland. Currently, forestation is significant in the western world, where land is being taken out of cultivation, while large-scale tropical deforestation is occurring because of logging, cultivation, and livestock uses (Bioscience 1994; Palo and Mery 1990). Taking both patterns of change into account, the annual global loss in forest cover may be as high as 100-200,000 km2 (Williams 1994).

If grassland is defined very broadly, it has changed little over the past 300 years, perhaps a net global decline of one percent (Richards 1990), as its loss to cropland (primarily in Europe, North America, and Southeast Asia) has been compensated by its gain from forest land (mostly in Africa and Latin America). If it is defined more narrowly (Graetz 1994), it has declined by some 20% since pre-agricultural times. More important than change in extent may be changes in the quality of grasslands and their soils.

The long-term, worldwide loss of wetlands is difficult to compute (Gosselink and Maltby 1990), although it is known to be extensive, possibly several million km2. Losses have primarily been the result of cropland expansion. Finally, rural and urban settlement now covers some four million km2 (Douglas 1994).

Two important patterns emerge from a brief review, with implications to which we return later. From the dawn of the Industrial Revolution until the early part of this century, major changes in land cover were centred primarily in the mid-latitudes of the Northern Hemisphere (v. Turner and Butzer 1992). Even where these lands have reverted to a cover type that existed previously, it has been in altered form. For example, the beech-hemlock-sugar maple forest of central New England that was cleared in the 18th and 19th centuries for farms, timber, and fuel has been replaced by birch, oak, hemlock, pine, spruce, and red maple (Foster 1993). During this century, and particularly in its latter half, the major land-cover changes have occurred in the tropics. In this realm, cropland and grassland/pasture expansion, deforestation, and urbanisation, among other changes, are increasing rapidly.

Land-cover changes, and therefore land-use changes, are environmentally significant in their own right. They degrade or enhance the land's capacity for sustained use and ability to regain its original cover. In some cases land-cover changes, or their impacts, can become so large or widespread that they are identified as global change in themselves. Elsewhere this kind of change has been referred to as globally cumulative change (Turner, Clark et al. 1990). Biodiversity loss is one example. Land-cover change has led to, or is leading to, significant losses in species numbers and varieties worldwide. Wilson (1992) estimates the loss in tropical forests alone to be on the order of 27,000 species annually, although much higher estimates exist (e.g., Ehrlich and Ehrlich 1981). Ecosystem structure and function, long-term ecological processes, and genetic diversity are also at risk in biodiversity loss. Biodiversity losses take place at multiple levels (landscape, ecosystem, species, gene) and in multiple dimensions (structural, functional, and processual) and, therefore, are particularly important for the structure and function of large-scale ecological processes, with implications for land use as well as other forms of global change (Schulze and Mooney 1993).

Impacts of Land Cover on Biogeochemical Cycles

Land-cover conversion is an important historical and contemporary component of other forms of global change (Leemans and Zuidema 1995). The historical conversion of natural systems to agriculture and other human uses of the land has resulted in a net release of carbon dioxide to the atmosphere (Houghton et al. 1985; Houghton et al. 1987; Houghton and Skole 1990), one roughly equivalent to the release from fossil fuel burning over the last 150 years, although the current release of carbon dioxide from land-cover conversion is approximately 30 percent of fossil fuel combustion. Land-cover conversion may have an important influence on regional climatology and hydrology (Shukla et al. 1990).

Both land cover and land-cover change data are important for determining the biogeochemical cycling of carbon, nitrogen, and other elements at regional to global scales. The estimates of carbon released from land clearing and biomass burning combined with the estimates of oceanic uptake of carbon cannot now be reconciled in a balanced global budget. The land estimates are either incorrect or incomplete.

Land-cover data are integral to analyses of other gas dynamics (Penner 1994). Natural ecosystems determine the dynamics of many important species such as CH4 and N2O. Ecosystem conversion results in changes in trace gas dynamics. Conversion of tropical forest to pasture seems to be an important factor in trace gas dynamics for years after pasture formation. Land is often converted through biomass burning, which may be an important source of CH4, CO, and other radiatively important trace gases (Crutzen and Andreae 1990).

The atmospheric concentrations of CO2 and other trace gases are closely linked to each other through their involvement with and interactions in chemical processes in the atmosphere (Prinn 1994). When compiling a list of the sources and sinks of these gases, it is apparent that both the land cover and land-cover change play major roles in determining their actual emissions and thus final atmospheric trace gas concentrations (Leemans 1995). Assessments aimed at evaluating the dynamics of global sources, sinks and fluxes of trace gases have to emphasise comprehensively the many different aspects of land-cover change (conversion, modification, and their characteristics) on many different spatial and temporal scales.

Land-cover change has an important influence on water and energy balance. Land cover determines surface roughness, albedo, and latent and sensible heat flux, and changes in the distribution of land cover alter the regional, and possibly global, balance of these fluxes. Such changes are important parameters for general circulation models. These models use coarse grids of 200 km horizontal resolution; because of rapid mixing in the boundary layer finer-scale data are presumably not required. Therefore, a general distribution of land cover might be sufficient. Nonetheless, the aggregate sum of various boundary layer transfers for each coarse grid would be dependent on a sub-grid parameterization. Latent heat flux, for instance, is mediated by evapotranspiration. Actual Evapotranspiration (AET), in turn, is a function of land-cover type, soil moisture, and climate (e.g., temperature).

Changes in vegetative cover, which mediate the water balance, also influence AET. Since AET is a function of whole plant and xylem water potentials, leaf area and stomatal closure, rooting depth, and canopy structure across the soil-plant-atmosphere continuum, water use and AET vary spatially across different ecosystems and temporally as one land cover is converted to another. They also vary as a function of seasonality. In these terms, geographically referenced actual land-cover datasets with a seasonality component are important for climate modelling beyond their simple utilisation as a means to parameterise sensible heat flux. Because the water balance and physiological controls on latent heat flux mediated by vegetation occur seasonally and at somewhat fine scales, there is a need to develop the appropriate datasets upon which coarse inputs to the General Circulation Models (GCMs) can be derived.

Part of the hydrological cycle involves the movement of water over continents. Plants act like waterpumps in this part of the cycle, extracting water from soils and returning it to the atmosphere through evaporation and transpiration. Water recycling in the Amazon rain forest is exemplary; the present precipitation patterns observed there are partly a function of the vegetation cover (Salati et al. 1979; Victoria et al. 1991). Changes in land cover, therefore, may trigger changes in the hydrological cycle which, in turn, would have significant implications for land uses. The impacts of the hydrological cycle caused by land-use/cover changes in the Amazon are not yet adequately assessed. One of the few such assessments (Shukla et al. 1991) indicates that a significant regional decrease in evaporation and precipitation would follow massive removal of forest there. At the global scale, land-use/cover change has been shown to have an impact on atmospheric circulation (Foley et al. 1994; Henderson-Sellers 1990, 1991, 1993; Henderson-Sellers, Wilson and Thomas 1985).

Land Use Links to Land Cover

Land cover may be changed by natural processes. Climate variations, of course, affect terrestrial ecosystems globally, while volcanic eruptions and changes in river channels or sea level have more localised impacts. Changes of these kinds are always operating and are, in some cases, difficult to disentangle from human influences, as in the case of desertification in the Sahel (Tucker et al. 1991). Regardless, the land-cover changes worldwide of the present and the recent past are overwhelmingly the result of human action - of activities largely aimed at modifying or converting land covers for the purposes of production and, to a lesser extent, settlement. These activities constitute land use.

The production-consumption demands of modern society cannot be met without major modification and conversion of land covers for various uses. Most of the uses fall into one or more of these broad categories: cultivation, livestock production, forestry/timber production, settlement (including transportation infrastructures and manufacturing), recreational uses/parks/preserves, mining, and, if near-shore environments are included, fisheries. The areas beyond frontiers, those yet to be substantially inhabited but not protected from settlement or use by a recognised political organisation, may be seen as areas that essentially lack an intended use. Of course, many such areas considered "open " have long been occupied and/or used at least ephemerally.

Every major category of land use has expanded significantly through human history and particularly since the Industrial Revolution. Currently, agriculture and livestock production have slowed in areal expansion globally, but with notable regional and sub-continental variations, while settlement expansion is escalating (Berry 1990). During the next decade and century, according to many experts (e.g., Ruttan 1994), agriculture will shift from expansion towards intensification, while urban areas, particularly along continental margins, will continue to grow. By the end of this century, most of the world's land area will be intensively and formally managed, and "open " lands will no longer exist. Moreover, much of world's prime agricultural lands will be increasingly influenced by local atmospheric pollution (Chameides et al. 1994.)

Specifying these trajectories of land-use change is essential to understanding land-cover impacts. Inasmuch as terrestrial ecosystems are spatially complex, land uses and land covers need to be matched by georeferencing. Any broad category of land use, however, includes many varieties of biophysical use of cover. Agriculture incorpo-rates uses as different as long-fallow slash-and-burn cultivation versus annual irrigated cotton farming, each with very different land-cover dynamics and global change impacts. Hence, locational specificity must be paralleled by use specificity.

Such specificity is difficult to achieve beyond the immediate future, however, because land use, driven by changing production-consumption dynamics, is subject to the vagaries and complexities of the social, political, economic, and even cultural and religious factors that give rise to those dynamics. Different researchers dealing with the social dynamics of land use draw different lessons for the level of detail at which they can be usefully modelled. Certainly models can be made more precise and accurate, particularly by incorporating subglobal components that capture regional and national variations in production-consumption dynamics and among land managers. What pass for land-use models are typically models of economic sectors predicting changes in production at the country level (v. FAO 1993a). They need to be better linked to outputs of locationally specific land use and land cover.

Land-Use/Cover Impacts on Sustainability

Changes in land use and land cover have significant environmental implications independent of the global variety, such as the direct use-cover impacts from soil degradation, surface runoff alterations, or the draw down in ground water. These kinds of changes - those confronting the land manager on a daily basis - as well as their impacts on, and sensitivity to, global environmental change are referred to here as issues of sustainability. We need not reiterate the magnitude, spatial scale, and pace of changes in sustainability inasmuch as they are intimately linked to, indeed often the same as, those detailed above for land-cover changes (impacts on states/faces and biogeochemical cycles). At least three points are important here. (i) Increasingly, the global environmental change community appears to realise the centrality of land-use/cover change in its own right to sustainability issues as recognised in the various outcomes of the United Nations Conference on Environment and Development in 1992. These sustainability issues link to developmental ones (e.g., AMBIO 1995; Chen and Kates 1994; Walker 1993). (ii) Many of the projected problems associated with land-use/cover sustainability, such as ground water depletion, may well trigger large-scale environmental problems in the near term that will have impacts on land-use/cover dynamics (Chameides et al. 1994; Graetz 1991; Tolba and El-Kholy 1992; Vitousek et al. 1986). (iii) The sustainability of any land-use is not only tied to the environmental attributes of the land and the techno-managerial strategies employed on it, but to the socio-economic condition of the land manager (Arizpe, Stone and Major 1994; Blaike and Brookfield 1987; Brookfield and Paddoch 1994). Land-use/cover sustainability, therefore, is largely captured in the kinds of integrated modelling efforts that are central to understanding land-use/cover change.

Modelling and Projecting Land-Use/Cover Changes

Modelling land-use/cover change has been approached in at least three different ways: through field-based case studies of land use; thematic assessments of the patterns of land-cover change; and prognostic, regional and global models of land-use/cover. Unfortunately, all have been stereotyped. Case studies and the models generated from them are too often equated with the specific-rich narrative, lacking generalities that can lead to macro-models; thematic assessments of cover change are considered too labour-intensive, too long on detail, and too short on explanatory power; and prognostic macro-models are criticised for their unrealistic assumptions and simplifications that preclude real-world usefulness, let alone accuracy. These stereotypes are not only unwarranted but miss the critical point that each approach complements, and, if integrated properly, improves the others.

Land-Use Dynamics: Land-Manager Studies

A global subject of study requires a large number of case studies comparable in structure and content, providing a firm empirical basis for characterising the major "situations " of land-use/cover dynamics. Case studies, along with spatial analyses from direct observation (cover pattern approach) can be used to build sets of micro- and meso-level models of land-use and land-cover change through time. The goals of such an approach are both description and explanation in the form of useful causal understanding (Clark, Jones and Holling 1979). The changes described by these models may be iterative, punctuated, or disjointed by historical periods. Mechanistic modelling based on cases adds to the credibility of larger models to the extent that it validates the broader-scale application of simple functional forms and aggregate parameters. Case-based empirical and qualitative modelling will advance understanding of LUCC if subnational and lower-scale (local and regional) models can incorporate local driving forces (such as culturally-specific institutions and/or policy intervention) in ways that global models will not.

Such an aim is new and challenging, both in its comparative dimension and its effort to join social science and natural science concerns. It constitutes a new analytical approach to land-use/cover change that transcends the divisions between natural and social science methodologies, addresses the cross-scale problematique directly, and offers empirically testable hypotheses about land-use situations in which both biophysical and human dimensions are represented as ever-changing forcing functions or driving forces.

The primary energy sources - solar, lunar, and geological - drive all the varied earth systems, including the human ones, whatever the convoluted transformations that take place within and across those systems. In one sense then, biophysical forces alone are the ultimate cause of both land-use and land-cover change. At temporal and spatial scales relevant to modelling human impact on land cover, however, these primary sources are apparent as an extraordinarily diverse set of driving forces that make up a distinctive "energy signature" for a given landscape, including both social and biophysical drivers (Odum 1983).

A view of nature as static (unchanging) or passive (changed only by social driving forces) is inconsistent with the notion of biophysical "drivers". Conversely, for an ecological determinist, society is the passive term, or dependent variable. The term "driver" or "driving forces" used here makes no claims as to first causes; it only stipulates that some land-uses/covers are strongly influenced in the long or short run by biophysical forces and some by social forces, and that the two should be considered jointly in analysis. These stipulations are made in a framework that recognises the relative dynamics of the interacting forces, so that variables that appear to be drivers at one scale may seem constant at another, and feedback effects are possible at scales other than that of the driving force. For example, the aggregate effect of groundwater withdrawal from individual wells may be coastal subsidence or a generalised desiccation of the landscape. By considering the cross-scale aspects and the biophysical and social driving forces together, the analysis framing in Focus 1 escapes the single equilibrium trap of some optimal models.

Analysis of LUCC, therefore, requires cross-scale dynamics and an historical dimension - not just human history, but natural history, too. An improved land-use change analysis must take into account the path-dependency of system evolution, the possibility of multiple stable states, and multiple trajectories. Land-use change cannot be simply explained as the equilibrium result of the present set of driving forces (Arthur et al. 1987; for an example, see Foster et al. 1992). In other words, land-cover type may be dependent on initial conditions, and small, essentially random events may lead to very different outcomes (Ruelle 1991), making prediction problematic. Exemplary is the effect of transportation infrastructure on the pattern of development. Road expansion and improvement not only lead to more development but may also lead to a different pattern through a reorganisation of market structure, which then feeds back to further infrastructure development. Thus, certain trajectories of land-use change may be the result of "lock in " that comes from systems that exhibit auto-catalytic behaviour (Arthur 1990; Arthur et al. 1987; Krugman 1991). Non-cyclic, path-dependent systems show three particularly troublesome properties for modelling and for policy: inherent non-predictability, potential non-superiority of outcomes, and structural rigidity (Arthur et al. 1987).

The complexity of the problem deepens with the understanding that three dimensions of drivers - socio-economic, biophysical, and land management (proximate causes) - are relevant to land-use/cover change, two of which involve adaptive agents and systems that respond to and sometimes anticipate changes in the other spheres. Global change modellers have only recently begun to deal with this problem with regard even to biotic feedbacks (Baskin 1993). An approach that integrates the three spheres, therefore, is not only necessary, it is forward looking.

A case study approach of LUCC needs to build on this view - the three dimensions as illustrated in Fig. 5. These forces may be put into historical and cultural contexts at various scales. The general idea is to compare geographically different but analytically similar land-use situations along these three dimensions. Each of the dimensions is implicitly multi-scalar, though in the context of global environmental change, the modalities of land management tend toward the micro-scale, whereas the biophysical and social forces are larger-scale processes expressing themselves in different ways across temporal and spatial scales (Fig. 6). In this perspective, the human dynamics of land-use change can be fitted to large-scale processes and to small, and the variable importance of human and biophysical forces that operate at different spatial and temporal scales will be more apparent. For example, cultural practices are important sources of variation in land management (proximate causes) at the level of the unit of production, and may endure over long periods of time, transcending shorter-term historical periodisation. Those important local variables may not be significant at the macro-scale (e.g., local practices in long-standing Amazonian settlements are not principal variables in the determination of overall Amazonian land use), and are generally dominated in a hierarchical system of political and economic power. A multi-scalar, hierarchical analysis is more likely to reveal the cross-scale changes in salience among such variables, as well as the emergent properties of systems at different scales.

Figure 7 reveals the concepts behind the three-dimensional approach. The drivers that determine land cover - proximal, social, and biophysical - are flows of energy or materials or information that arise from identifiable systems or agents. In dynamic modelling we are likely to associate land users (the human agents of land manage-ment) with modalities, institutions and macropolitical frameworks with social drivers, and physical and ecological systems with the biophysical drivers.

Each suggests some differences in methodology. To model proximal drivers (those factors most immediate to the actual change), for instance, one would want to model the agents behind them, since it is their perceptions and decision-rules in the context of the "exogenous" drivers that determine their actions. At the macropolitical level, a choice-oriented perspective is more limited by various structures (e.g., organisations, institutions, system constraints).

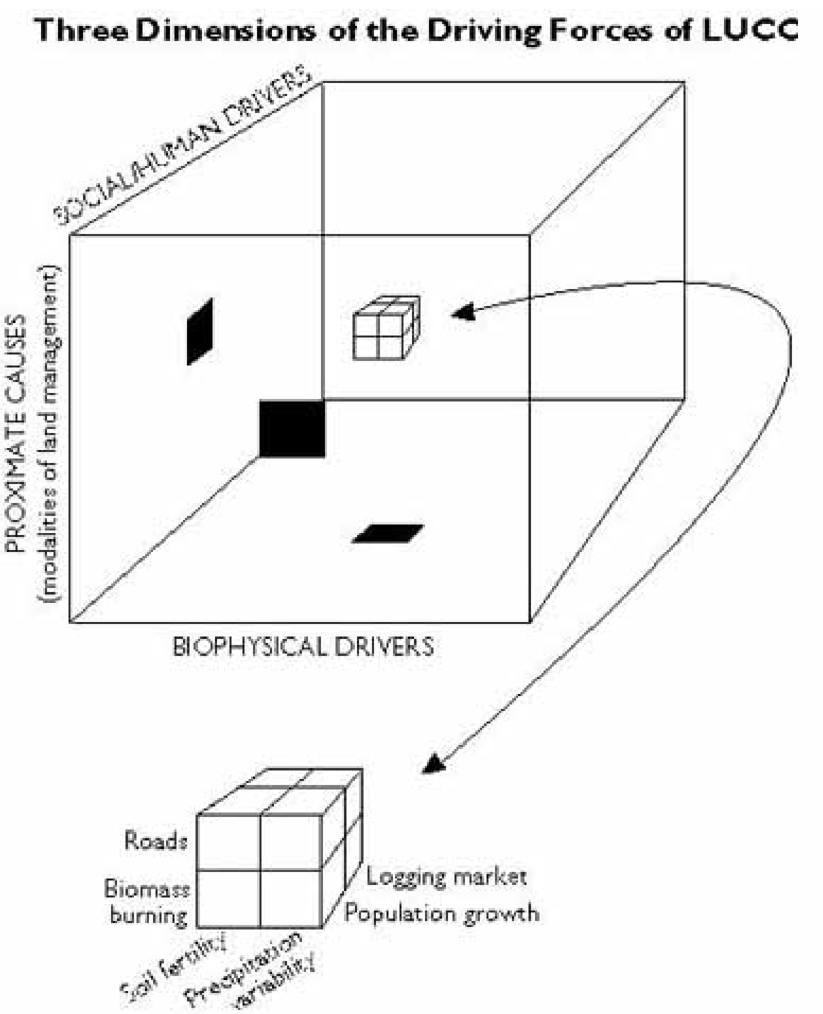

Figure 5. Three Dimensions of the Driving Forces of LUCC.

Our approach indicates that land cover changes in multiple ways (Fig. 8). It can change as a result of (i) independent changes in biophysical drivers (e.g., climate and atmos-pheric change, natural erosion and deposition), (ii) human activity, either direct alteration (e.g., deforestation) or (iii) mediated through the biophysical realm (e.g., groundwater withdrawal leading to a lowered water table and to reduced stream flow and altered vegetation), or (iv) a more complex chain of human activity in the biophysical world, which feeds back to human activity, which then directly alters land cover (e.g., human introduction of rinderpest, change in wild herbivore population, advance of woodland with tsetse, leading ultimately to mechanised clearing: Sinclair 1979).

There are two steps in the case study approach to disaggregating the problem. The first, as noted, is to divide forcing functions into social and biophysical drivers and proximal drivers. The second is to analyse each set of drivers in terms of spatial and temporal scale in an attempt to resolve at least some of the complexity and controversy regarding multiple driving forces. This step draws on Holling's argument that the dynamic behaviour of many ecological systems can be explained by a few driving forces operating at characteristic frequencies and spatial scales - the extended keystone hypothesis (Holling 1992). Is it possible to find such keystone processes in the complex tangle of driving forces and systems in land-use/cover change? This query is central to the modelling of land-use/cover change at the global and smaller scales.

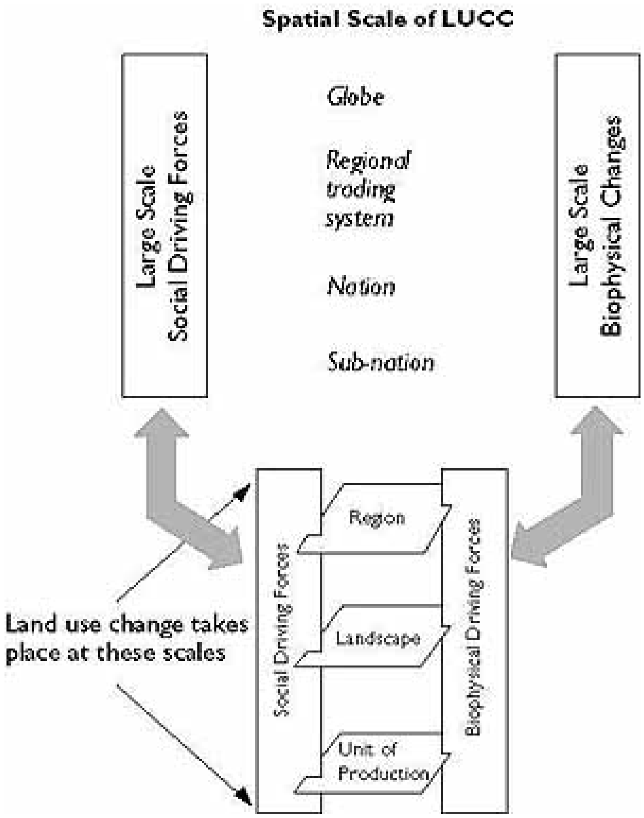

Figure 6. Spatial Scale of LUCC

A case study approach provides a testing ground for predictions of use/cover change from global and regional modelling efforts. More than that, it can provide the empirical basis for confidence limits on model predictions which at an aggregate level are bound by ceteris paribus restrictions that prove debilitating in a ceteris non paribus world. Structural change cannot be predicted or even anticipated in such models, and theoretical associations may or may not hold up under changing conditions. Case-based mechanistic modelling can discriminate between valid and spurious correlations, and the development of use/cover situations can provide a basis for scenarios detailing the multiple pathways of land-use/cover change.

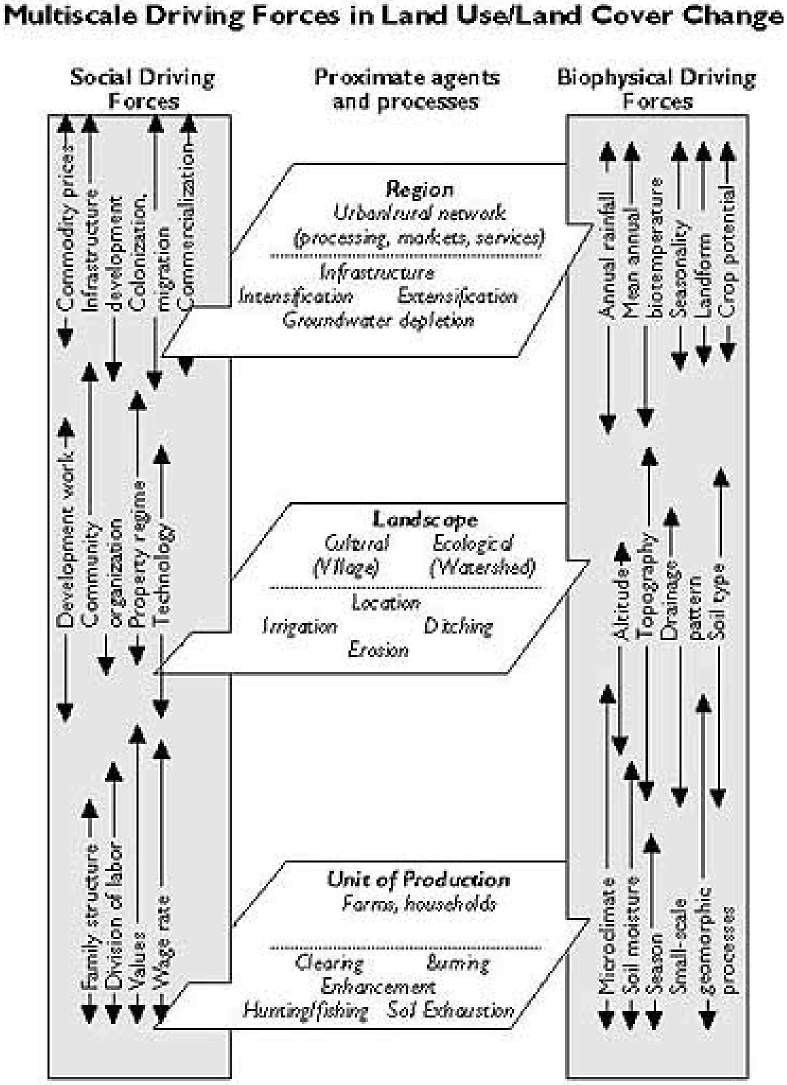

Figure 7. Multiscale Driving Forces in Land Use/Land Cover Change

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Land-Cover Dynamics: Diagnostic Models from Empirical Measurements

Another major approach to understanding land-use/cover change involves the use of direct observations from a variety of empirical sources of land-cover change, including satellite remote sensing, national censuses and land-cover inventories, and field-based measurements. These observations can be used to directly calibrate empirical, spatially-detailed models of land-cover change (Lambin 1994).

This approach has a twofold emphasis. First, it emphasises the need to make observations with the appropriate frequency and spatial scale to explicitly quantify land-cover change and land-use distributions. These observations provide a foundation upon which a range of models can be calibrated or validated. To the extent that these measurements can provide quantitative measurements of spatial patterns of land-cover change, they provide additional important information for: (a) analyses of spatial relationships between land-use and land-cover change, (b) analyses of land cover and landscape fragmentation, (c) analyses of spatial trends and spatial diffusion of land-use/cover change, and (d) a suite of other geographically-specific dynamic analyses. Second, spatially explicit direct measurements of land-cover change can be used in conjunction with other forms of geographical or spatial information to develop diagnostic models of land-cover change over time. Associated spatial information related to the physical environment (e.g. soils, vegetation, topography) and socio-demographic conditions (e.g. population structure, economic activity, land tenure) can be merged with the data on land-cover change to develop empirical models with limited capability for predicting land-cover change over short intervals. These models would provide a basis for defining the contemporary land-cover change (i.e. last 20 years) to begin to close the carbon budget regionally and globally, and would also provide short term predictions (next 20 years) in support of vulnerability assessments and other forward-looking analyses.

The Land-Use and Land-Cover Projections Working Group of the OIES Global Change Institute on Changes in Land Use and Land Cover provides a review of an approach to empirical, diagnostic modelling of land-cover change (Robinson et al. 1994). Their conclusion was that relatively simple empirical studies are preferable to more complex global modelling. Many of the basic forces that drive land-use/cover change operate on time scales of decades rather than years. These include population size and geographic distribution, technological options, income and income distribution, transportation infrastructure and other variables. A methodology which captures simple, strong relationships and the impact of development sequences is likely to succeed reasonably well as a structure for projections for periods of decades. Thus, the development of empirical models provides an approach for both extrapolations during the period of existing measurements and projections of trends beyond the period of measurement.

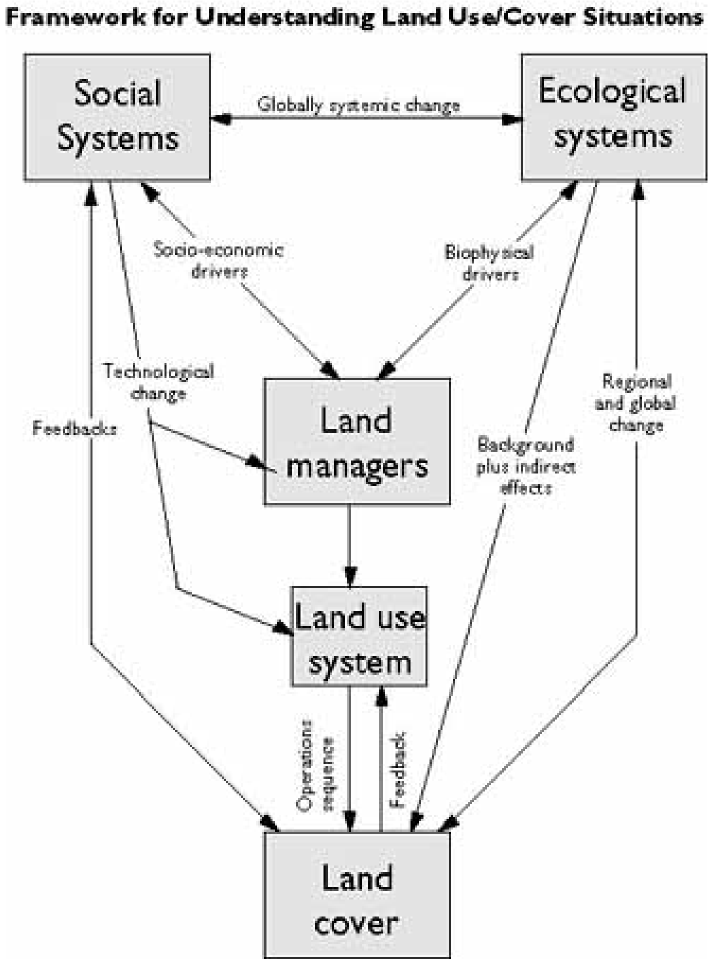

Figure 8. Framework for Understanding Land-Use/Cover Situations

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This approach assumes that the forces which dominate during the period of observation and calibration would persist throughout the period of projection or extrapolation. Such models based on the assumption of persistence are reasonably predictive, particularly over intervals of a few decades. There is an emerging body of literature which suggests this approach is feasible (v. Lambin 1994). For instance, there is evidence that deforestation in tropical forests is persistent spatially and temporally for up to 10 years. More work must be done on defining the parameters and approaches for different regions and ecological zones. While such models are probably viable for deforestation, further development is necessary for other types of land-cover change. Even so, such models provide no information about the underlying driving forces, even if they may provide key insights or correlation to driving variables. Thus, this kind of modelling needs to be tightly coupled to case study analyses (see above). With added information on causality, these models can be integrated with case-study-based rate modifiers which limit or expand the spatial and temporal trends of the empirical model. The OIES Global Change Institute on Changes in Land Use and Land Cover Working Group on Land-Use and Land-Cover Projections recommended a range of information which can be obtained from case-study based analyses to enhance empirical models.

An important aspect of this approach is the development of verifiable models of land-cover change during the period of time in which other global change models (e.g. global carbon models) need information on the land-cover change forcing function. One aim of current global change research is to build a comprehensive understanding of the linkage between three important areas: (a) global climate, (b) global biogeo-chemical cycles, and (c) global water and energy balance.

There are two general requirements for integrated global change models of this type. First, it will be necessary to develop models in which actual, rather than average, conditions and parameters are used. For example, to close the global carbon budget actual estimates of climate, atmospheric concentration of carbon dioxide, oceanic uptake of carbon dioxide (CO2), and biotic fluxes - both natural and anthropogenic - will need to be integrated simultaneously into a model framework. It will not be sufficient to use decadal mean values; matching model results and atmospheric measurements over the last twenty years of atmospheric measurements requires estimates of the actual, time-dependent land-cover forcing. The objective of such an exercise would be to link annual changes in land cover to annual measurements of atmospheric concentrations and other components of an earth system model. Another example would be the case of ENSO (the El Ni–o - Southern Oscillation phenomenon), where it would be necessary to know the actual land use and cover change responses to this short term, but globally significant, climate perturbation. The average annual rate of land-cover change will not be a good indicator of the land-cover and land-use response to a change in climatic patterns in a particular year.

Second, it will be necessary to have explicit information on the spatial and geo-graphical distribution of land-cover change with a high degree of spatial resolution. For example, the effects of land cover on energy balance and water flux are a function of the size and spatial arrangements of land-use and land-cover changes. As another example, sediment delivery rates are related to where in the watershed land-cover change is occurring, as a function of stream order, slope, and other geographically-specific factors.

There are other requirements for spatially explicit models and estimates of land-cover change. Attempts to develop global budgets of important trace gases, such as nitrous oxide, suffer from the lack of spatial data. Frequently, regional extrapolation of trace gas fluxes has been based on representative, or average, in situ measurements. Matson, Vitousek and Schimel (1989) argue that global budgets could be improved by accounting for spatial and temporal variability, and support analyses based on spatial gradients, from which functional relationships between fluxes and land cover, climate, and disturbance could be derived.

The spatial arrangement of land-cover conversion, particularly deforestation, also influences results of model simulations of continental-scale climate and energy balance. Deforestation distributed as a few large blocks may have greater influence on sensible and latent heat flux than the same distributed as many widely scattered small patches (Henderson-Sellers 1987; Henderson-Sellers and Gornitz 1984).

Finally, there is increasing concern that land-cover conversion in humid tropical forests will result in the loss of a significant number of species (Ehrlich and Wilson 1991). The impact on biodiversity is related to the total area of forest conversion and the amount of forest fragmentation. Quantifying fragmentation requires an understanding of the spatial arrangement of cleared areas (Soule 1991; Wilson and Peter 1988).

Knowing what cover occurs where, its spatial characteristics, and its trajectory of change, therefore, is crucial to much research on global change. Yet, at this time, little is known about the coincident distribution of land cover, land-cover attributes, and land-cover conversion. We know even less about the geometry and spatial organisation of land-cover conversion. New initiatives must focus on spatial and temporal characteristics of both natural land cover and conversion activities. These initiatives are particularly important for the contemporary period (the last 20 years). Efforts to balance the global carbon cycle will require spatially disaggregated results that can be coupled directly with terrestrial ecosystem models, general circulation models, direct observations of atmospheric carbon dioxide, and climatological data acquired during the period of observation. The need for such work based on high spatial resolution for the last 20 years and five to ten years hence is noted by the Framework Convention for Climate Change and the IPCC.

Most of this work to date has focused on land-cover conversions, which are empha-sised here, although in principle it can be expanded to include cover modification as well. This emphasis is understood in terms of the significance of the conversion process to several global change themes. The current conversion of tropical forests to pasture and cropland, for instance, contributes as much as 30 percent of the net flux of carbon dioxide, even though the rate of forest conversion is less than one percent/ annum. In other words, comparatively small amounts of conversion of some covers can have significant environmental impacts.

Integrated Regional and Global Modelling

A major aim of the LUCC effort is to extend understanding of cause-use-cover dynamics to improve regional and global models and projections of these dynamics. Model systems must be developed that are geographically sufficiently disaggregated (e.g., province, sub-national or national models for describing economic systems) but can be aggregated to the global, are multi-sectoral and sensitive to the non-linear and interrelated driving forces of land-use and land-cover change, account for major biophysical feedbacks, and are capable of coupling to biophysical models, such as global circulation models (Frederick and Rosenberg 1994; Riebsame et al. 1994; Riebsame, Meyer and Turner 1994; Robinson et al. 1994; Turner 1994). It is difficult to conceive of any other mechanism than models for projecting the impact of such a complex matrix of driving forces and biophysical feedbacks. Such models, if constructed properly, are not limited to land-use and land-cover change, but can provide the quantitative framework for scenario analysis relating to climate change, hydrological cycles, biodiversity, sustainability, and food security as well as general changes in tastes, values, and norms of society.

LUCC models should be crafted so that they can handle the major directions that land use and cover and their dynamics appear likely to take over the next 50 to 100 years, and yet be capable of dealing with the surprises that will surely occur. Some of the major directions are especially clear. World population growth alone together with expected levels of economic development will fuel increasing demands for land-based resources. These demands will drive the expansion of certain land uses, but given that most of the world's potentially prime agricultural lands are already in production (FAO 1993a, Crosson and Anderson 1992), major intensification is inevitable within classes of land uses, such as the intensification of crop cultivation. Development, or, more broadly, modernisation, is changing the structure of economies and settlement. An increasingly significant proportion of land-use and land-cover change is a result of urban demands for agricultural or forest products rather than rural subsistence needs. Currently, at least 25% of the world's population is engaged in peasant agriculture (Cancian 1989), covering a significant proportion of the earth's land surface. Therefore models must be able to account for partial- or non-market conditions. On the other hand, 44% of the world's population lived in an urban setting in 1990 compared with 34% in 1960 (Simpson 1993). By 2025 the proportion will have grown to 60%, and by 2050, it is estimated that more than 75% of the developing world's population is likely to be urbanised, less than 25% being economically active in agriculture. Thus land-use/cover change and particularly land-use practices will increasingly be affected by what is happening in the urban economy. Models must capture the spread of market systems. If by 2050 much of the world's agriculture is largely commercialised, then land-use decisions and resulting land-cover in this sector will primarily be price- and wage-driven (Parikh et al. 1988).

Until the early part of this century, almost all of the increase in food production was obtained by bringing new land into production; by the end of this century, almost all of the increase in world food production comes from higher yields (Hayami and Ruttan 1985). For example, the FAO estimates that about 80 percent of agricultural production increases in developing countries (excluding China) between 1990 and 2010 will result from yield increases and intensification of land use; arable land use in these regions will expand by about 12 percent (FAO 1993a: 104). In developed countries, agricultural productivity increases are likely to command a decline in agricultural areas as was the case in the recent past.

Technological change has been and will remain central to the intensification in crop production. In many existing models, the process by which technological change is induced has been treated as exogenous to the economic system. Advances in theory and the accumulation of empirical evidence, however, suggest that technological change is largely induced endogenously (e.g., Hayami and Ruttan 1985; Binswanger and Ruttan 1978; Pingali et al. 1987; Tiffen and Mortimore 1992; Turner et al. 1993). Pressures from environmental constraints drives technological innovation. Given that technological change is an essential element of growth, thereby also a major determinant of future land-use, it will be necessary to introduce the mechanisms of technological progress dynamically into the land-use and land-cover model.

The prototypical actors in the social and economic systems - producers, consumers and governments, to name three - act with more or less foresight, depending on the severity of individual short-term constraints, amount of information available to them, and the prevailing value systems. The value and use of land, as well as the quality of other resources, like water, forest, or mineral resources, are critical to the discussion of viable and sustainable economic development, environmental change and pollution control strategies. The production potential of agricultural resources is often reduced by physical and chemical degradation, and may be at risk for negative impacts from potential climate change. On the other hand, agriculture itself may generate pollution, affecting, for example, water quality and tropospheric trace gas concentrations. Environmental protection and improvement can be achieved through various countermeasures, such as land-use regulation, purification technolo-gies, clean-up, and emission control strategies. Consequently, it is important that the models are able to represent such policies as well as other policy alternatives, such as investment in infrastructure of a region or investments in land reclamation and improvement.

Any discussion of human interactions with the environment must also come to grips with uncertainties and resulting risks. Strategic decisions can result in virtually irreversible impacts, such as constructing a dam, clearing rainforests for agricultural purposes, or diverting agricultural land to urban and industrial uses. At the time of decisionmaking, there is often considerable uncertainty regarding future economic costs and benefits as well as possible environmental risks. Concepts dealing with foresight, uncertainty and risk must be given due consideration in designing LUCC model systems geared towards long-term projections of human-environment interactions.

Biophysical feedbacks play a critical role in long-term dynamics of land use and land cover, but there is no consensus on their strength or temporal and spatial scales. For example, estimates of soil erosion losses and their implications for long-term agricultural productivity and land-cover change may have been exaggerated. The UN estimates of desertification (UNEP 1987; UNEP/GEMS 1991) and others on global soils loss (e.g., Rozanov et al. 1990) are not without critics who suggest that not only are these estimates inflated but the economic risks of soil loss have been exaggerated (Hellden 1991; Graetz 1994; Crosson and Stout 1983; Rhodes 1991). Some earlier observers suggested that overgrazing in parts of Africa would shortly destroy the landscape for that activity, but other assessments taking account of traditional management practices, local soil conditions, and the spatial characteristics of soil erosion and deposition suggest that substantial land-cover degradation and change at the sub-continental scale are 100 or more years away (Biot et al. 1992), though this does not mean that there is no ecological degradation (de Queiroz 1993).

Over a long time span, there may be major changes in the driving forces, some of which are likely to be positive rather than negative for land cover (e.g., improvements in management practices and reduction in the human population directly dependent on crops or livestock for subsistence or cash income). The critical point here is that models must be able to handle major variations in the biophysical impacts and feedback of land use, and their projections must incorporate both negative and positive biophysical considerations. They must take note of: (i) the vagueness of definitions about cover or cover impacts; (ii) the uncertainty of causes, human or physical, and their linkages; (iii) the uncertainty of estimating or projecting impacts into the future; and (iv) the difference between short-term human responses and longer-term adaptation and innovation.

Finally, it is increasingly clear that supply of and demand for water from agriculture, in particular for irrigation, will be critical elements of the land-use dynamics in certain regions, such as West Asia and semi-arid Africa. Agriculture accounts for as much as 70-80 percent of water use worldwide (e.g., Kulshreshtha 1993), and other sectors are competing for more water resources as countries develop. In some countries a very high proportion of cropland (e.g., shares of cropland irrigated in 1989 were: Egypt 100%, Pakistan 78%, China 47%, Iraq 47%, World 16% [Postel 1992]), and even a greater proportion of crop production, depends on irrigation. The increasing shortages in the coming decades projected by a number of water-use assessments hold major implications for land-use/cover change (Postel 1992; Gleick 1993; Kulshreshtha 1993). Moreover, these shortages may be amplified by land-cover change, notably deforestation, and by possible global warming. Consequently, the land-use/cover change models need to address two specific aspects of the water sector: (i) the mechanisms of water distribution and use, i.e., institutions, water rights and pricing mechanisms, and (ii) linkages of land-use and land-cover change to variability and change of stocks of usable water resources. Very few global agricultural models have attempted to do so since the Systems Analysis Research Unit Model (SARUM) of the mid-1970s, which had a water development sector (HMSO 1977), and included irri-gation in the agricultural production function (v. FAO 1993a). Fortunately, however, a number of effective approaches at the national, sub-national, and watershed levels point the way for more comprehensive attempts (e.g., Strzepek et al. 1994).

With these characteristics in mind, it is hardly conceivable that a single model is capable of providing a comprehensive global yet geographically detailed assessment of land-use/cover change. LUCC-related global-scale models are not without exemplars, however. These models were generally built for specific purposes and have applied a wide range of methodological approaches and theoretical rigour. Several examples illustrate.

The impacts of climatic change on the location and extent of natural ecosystems (e.g., Bultot et al. 1992; Emanuel et al. 1985) and agrosystems (Parry et al. 1988a,b) have been analysed. These static studies conclude that large shifts could occur with immense consequences for current land-cover patterns and agricultural potential. The climatic change studies address only a few aspects of the earth system, but have been improved by including the transient response of eco- and agrosystems and accounting for the direct effects of increasing atmospheric CO2 (e.g., Solomon 1986). None of these studies accounted explicitly for changes in land use, however; they were attempting to assess the impact of global climate change.

Among the first global change models was the Integrated Model to Assess the Greenhouse Effect (IMAGE 1) (Rotmans 1990; Rotmans et al. 1990). This model aimed to project the concentrations of different GHGs in the atmosphere for the period 1900 to 2100. IMAGE 1 consisted of a series of highly aggregated sub-models including an energy-emissions module, carbon cycle models, an atmospheric chemistry module, and so forth. The model was driven by different population and energy scenarios, and it simulated the trends for atmospheric concentrations of different greenhouse gases, from which a global mean temperature change was computed. The approach of this model led to the development of the ESCAPE framework (CRU and ERL, 1992), in which a more advanced climate module allowed for linkage of several different impact modules: sealevel rise, agriculture, and ecosystems. These models had major disadvantages with respect to changes in land use and their human causes. Changes in land cover were prescribed, often only accounting for tropical zones, and few cover types were represented. Deforestation rates were mainly extrapolations of the high rates listed in the early 1970s and 1980s, while current rates have decreased (Skole and Tucker 1993). Furthermore, the consequences of the impacts of global change did not feed back into the causes neglecting important feedback mechanisms (Vloedbeld and Leemans 1993).

An ambitious attempt to model complex relationships between agriculture and the rest of the economy was the IIASA global model of the world food and agriculture system (Fischer et al. 1988). It consists of a number of linked national models based on welfare economics and applied general equilibrium (AGE). The model system includes the dynamics of population and rural-urban migration, socio-economic factors, capital accumulation, and market clearing conditions to project demand, supply and agriculture land use at aggregate national level. Recently, elaborate process crop models (IBSNAT 1989) have been coupled to the IIASA model (Rosenzweig et al. 1993; Fischer et al. 1994). Although these studies were rather detailed and covered large regions, they emphasised global change impacts on agriculture only and did not assess future changes in land-use and land-cover of other sectors.

Another example of a long-term bioeconomic assessment with reasonable geographical detail was the spatial equilibrium model formulated in a study of the economic effects of global climate change on U.S. agriculture. The model represents production and consumption of 30 primary agricultural products including both crop and livestock products. The model consists of two components, a set of micro- or farm-level models integrated with a national sector model. Production behaviour is described in terms of the physical and economic environment of agricultural producers for 63 production regions encompassing the 48 contiguous states of the United States. Availability and use of land, labour, and irrigation water is determined by supply curves defined at the regional level.

An integrated economic analysis of the potential impact of global warming on a four-state region of the United States (Missouri, Iowa, Nebraska, Kansas) is known as the MINK study (Rosenberg and Crosson 1991). The study team has included four sectors of the economy (agriculture, forestry, water, and energy) in the analysis, and aims for a spatial representation of the mutual relationships and interdependencies between these sectors and climatic conditions.

A different set of models was developed to assess availability of natural resources suitable for food production and forestry. The basis of many of these models was the Agro-ecological Zones approach developed by the FAO (FAO 1978; FAO/IIASA/ UNFPA 1982; Brinkman 1987; FAO/IIASA 1993). The approach assesses the local suitability to grow crops on the basis of climate, soil and crop characteristics. The approach was used in several applications; for example, to analyse land use in the context of national development planning (FAO/IIASA 1993) and to determine crop distribution and yields under different climates (Leemans and Solomon 1993).

A global integrated system that addresses explicitly changes in land use and cover is the IMAGE 2 model (Alcamo 1994). It includes a rule-based land-cover change model that is linked to the changing demand for agricultural commodities (Leemans and van den Born 1994; Zuidema et al. 1994). The model aims to simulate the transient dynamics of atmospheric greenhouse gases, accounting for the major interactions within the earth's system. The human driving forces are derived from exogenous scenarios for demographic, economic, and technological developments, which are implemented for a number of broad aggregate regions. However, these exogenous forcing functions affect the land-use system without accounting for demographic, economic, or technological feedbacks in response to simulated scarcities.

Most of the livestock models and the underlying vegetation dynamics models of those linked explicitly to rangeland management are too static, too partial, or too micro to provide a starting point for land-use and land-cover change modelling. They tend to be location-specific or to focus on biophysical relationships to the exclusion of livestock/grazing land management and socio-economic aspects. Nonetheless, some of them contain lessons and approaches useful to land-use and land-cover change modelling at higher spatial scales. Thus, although FLIPSIM (Firm Level Income and Policy Simulator Model) (Richardson and Nixon 1986), which is a dynamic, stochastic simulation model, was developed originally for micro-level analysis, it lends itself to scaling up to the regional or national level through the representative farm approach. Representing an ecological modelling approach, vegetation cover and soil organic matter dynamics in managed (and unmanaged) grassland ecosystems can be assessed with the CENTURY model (Parton et al. 1987; Parton et al. 1993). Related to this is SAVANNA (Coughenour 1993), a process-oriented model of pastoral ecosystems that could be applied to larger regions.

At the national and regional scale, there are forest models that contain more detailed treatment of the socio-economic driving forces for land-use/cover change and notably for human colonisation and deforestation (e.g., Grainger 1990; Southworth et al. 1991; Dale et al. 1993). Some of them are spatially explicit and contain feedback relationships to simulate the impact of land-use on sustainable development. In the main, however, the feedback relationships in both small- and large-scale models tend to be uni-directional, with little, for example, on how the biophysical side of the model affects the socio-economic. A recent review of modelling approaches applicable to deforestation processes can be found in Lambin (1994).

Appropriate LUCC models will require the kinds of improvements noted above. Fashioning them and assessing their contributions to the robustness of the models do not pose insurmountable problems. The complexity of the problem and past modelling experience suggest that for a comprehensive assessment and projection of land-use and land-cover change a variety of models will need to be developed and integrated. Figure 9 shows a generic integrated LUCC model system indicating several important components: a demographic component and modules for representing changes in social expectations/ values and policy settings, an economic model, a land-use allocation component, models of resulting land cover and environmental impacts, and a land productivity module, feeding the simulated impacts back into the economic and other social components, thereby closing the feedback loops. The task is to select or develop models that are appropriate to the specific questions asked, methodologi-cally consistent when coupled, and compatible in time and spatial scales. Importantly, the land cover and environmental impacts, land productivity, and climate system modules as depicted in Fig. 8 should link directly to other global change models, including those developed through the IGBP.

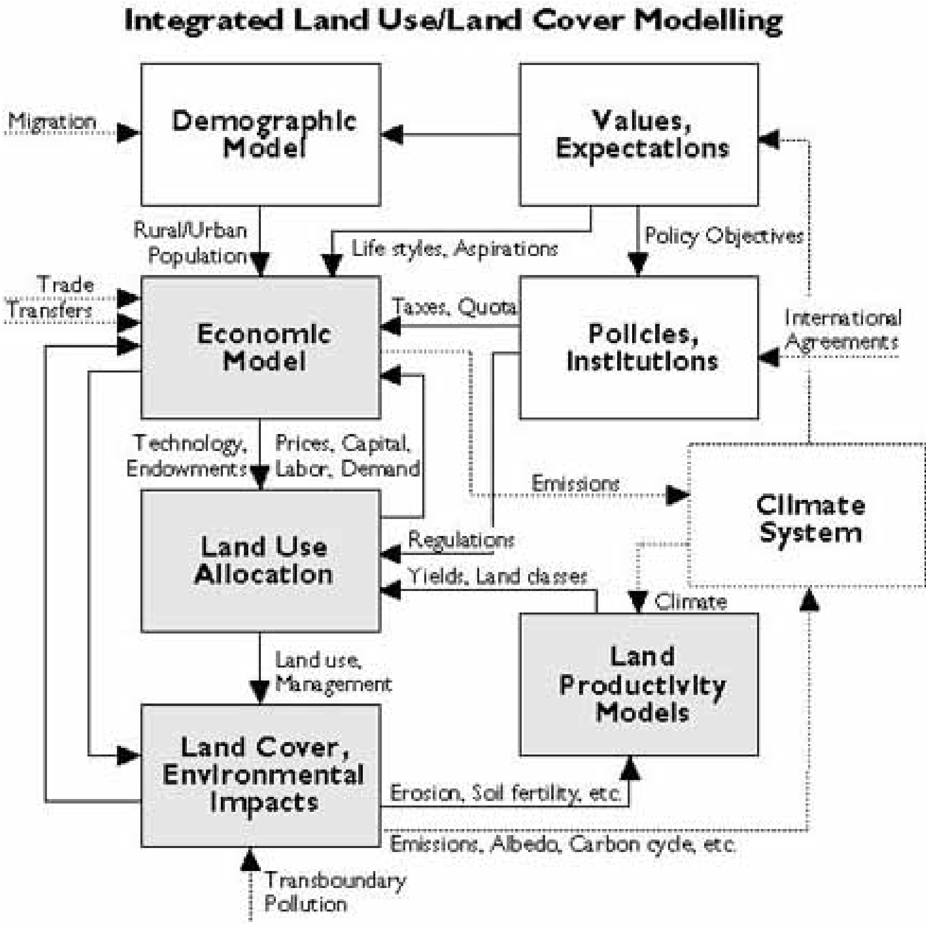

Figure 9. Integrated Land Use/Land Cover Modelling.

Lastly, the questions of sensitivity analysis and model verification and validation are of importance in the deliberations of Focus 3. It is commonly agreed by modelling methodologists that model validation is one of the most important stages in the model building process. Despite this agreement, formal methods of model validation only exist for certain types of models, usually those applied to systems that exist in the real world and where it is possible to conduct a series of active experiments. In such cases statistical methods can be used for validation (e.g., Schruben 1980). Many authors point out that model validation should be goal-oriented (Lewandowski 1981). In the process of developing LUCC models different situations will arise. Some models will serve to improve our understanding of certain processes. Other models, specifically those developed in Focus 2, can be used for short-term forecasting. In the process of generating long-term LUCC projections, models will be used for scenario analysis and normative goal-seeking (e.g., optimisation). The validation methods to be applied will have to vary with the type of model being used. In many cases formal validation methods will not be available. In such situations, the necessary validation needs to stress: (i) rigorous testing of specification and methodological foundation of the models; (ii) thorough testing of model sensitivity with respect to parameterization including backcasting; (iii) sensitivity of model results with respect to quality of used data sources; and (iv) econometric estimation of parameters as warranted by quality and amount of available data.

Issues of Spatial Scale

Understanding the local, regional, and global dynamics of land-use/cover change obviously requires crossing spatial and hierarchical (as well as temporal) scales (Figs. 6-8). At present, our understanding of the links between scales is poor. Yet, it is well known that changing the spatial scale of the analysis may change the result (e.g., Meyer et al. 1992). Many global and large-scale sub-global analyses identify variants of the so-called PAT variables (population, affluence, and technology) as having the strongest statistical correlations with environmental change (Bilsborrow and Okoth-Ogendo 1992; Rudel 1989), often implying that the specific variables in question are the underlying driving forces of change. Local case studies, however, do not always concur. Indeed, if a common theme emerges from them it is that the PAT variables are much less important in LUCC than institutions, policy, or other such variables of social organisation (e.g., Arizpe, Stone and Major 1994; Kasperson et al. 1995; Zaba and Clarke 1994). Alternatively, in these cases, PAT variables may have a delayed or mediated association that masks their influences.

Why this is so is not well understood. It may reflect the biases brought to the study by those engaged in either scale of analysis, a conclusion that, if substantiated, would be of no minor significance. It may also reflect problems of aggregation/disaggregation. There is yet a more profound possibility, suggested by, but not dependent on complex systems theory. Such a possibility can be summed up in a few straightforward but empirically vexing principles. These are:

(i) That natural and social systems at different temporal and spatial scales are imbued with different kinds and degrees of organisation. This allows us to treat the scales of social and natural systems together only in certain circumstances. Fossil fuels pose a considerable problem for linking social to natural systems, for example, since they allow the focusing of concentrated energy from a much larger scale in the past.

(ii) That such organisation of systems, both natural and social is loosely hierarchical; that is, systems are funcionally or operationally layered in their relationships with one another. The description of such hierarchical relationships is important.

(iii) That the relationship between scales of organisation (cross-scale dynamics) is unknown but important to determining scale boundaries and the influences of key variables on emerging properties at different scales. Scales of organisation are not the same as scales of observation (level of analysis).

(iv) That temporal scales are more than simply chronological, and must account for natural and social history, with their implications for qualitative shifts in land cover and use through time. This suggests recourse to notions of path-dependent change and limited reliance on single-equilibrium models or those tied to time as a simple chronological index.

These issues are complicated by the fact that spatial, hierarchical, and temporal scales must be understood in terms of their real world, measured (empirical), and modelled contexts. Real world scale effects exist in all land-use/cover phenomena but can only be assessed by actually measuring their properties. Since all such phenomena and properties cannot be measured, we are limited to empirical scales, which are, in a sense, subjective because of the choice of data and the selected spatial and temporal (also hierarchical) scales. Similarly, models are generally only valid for given, well-defined scales. Thus, LUCC must pay considerable attention to the systematic assessment of empirical and model scales. Case studies must be selected in such a way that they can be scaled up to less detailed levels.

LUCC research is confronted with two different scale effects that must be taken into account: (i) each scale has its own specific units and variables; and (ii) the inter-relationships between sets of variables and units change with scale. How can valid regional models be developed and linked to global models given these effects?

The solution lies in the development of a truly hierarchical approach in both observation and explanation of the processes of land use/cover change. As different scales allow us to answer different questions, explanation of land-use drivers can only be achieved by combining observations and explanations from different levels of the scale hierarchy. A comprehensive study of LUCC requires a nested set of scales and corresponding data. Once scale effects are known and quantified, models can be made for each measured scale level. The scale hierarchy then functions as a key for cross-scale dynamics.

The following example is drawn from a study of the drivers (or exogenous variables) of land-use/cover in Costa Rica (Veldkamp and Fresco 1995), with drivers selected from environmental, population, and agricultural classes. The population and agricultural data for 1973 and 1984 were taken from the country's census and converted into grid cells. The selected minimum grid size (0.1(geographical grid or about 7.5 km x 7.5 km or 56.25 km2) was based on the estimated average district size or the finest resolution possible with the census. These data were matched with biophysical map data converted to similar grids. The 0.1(grid data were aggregated into five larger grids of 225 km2, 506 km2, 900 km2, 1,406 km2, and 2,025 km2 or 4, 9, 16, 25, and 36 grids respectively on the x-axes of Fig. 10.

Multiple regression models were made for the six spatial scales for each available year to explain the variance of major land-cover classes. Here we illustrate using permanent crops.

Regression models of the drivers of permanent crops showed varying fits (30% to 75%) with spatial scale for both years (1973 and 1984), but a maximum fit was observed for the same range of aggregation level (506 km2 and 900 km2) (Fig. 10). In 1973, the relative relationships between the driving forces and permanent crops showed that the agricultural labour force had a strong positive relationship with permanent crops, while urban population had changing negative and positive relationships, and relief displayed only a slight positive relationship. These findings varied little by spatial scale. The data, however, show a clear change in the relative contributions of the driving force by spatial scale. The positive contribution of agricultural labour decreased with an increase in spatial scale, while urban population switched from strongly negative to a positive relation with scale increase - a change in model fit and variable contribution with spatial scale. The scale of 506 km2 (9) revealed a completely different picture from that for 2,025 km2 (36). The explanations for these differences are not important for our purposes here; the important point is the relationship between spatial scale and statistical outcomes.

Without specific attention to scalar dynamics, as illustrated for the Costa Rican case, a number of research possibilities might be ignored to the detriment of the study of land-use/cover change. In this example, for instance, the influence of global agricultural prices on cropping decisions by local agriculturalists is empirically unclear, but often modelled as a given relationship from global to local scales. For land use and cover to be integrated across those scales, static model parameters must give way to plotting specific cross-scale transformations, which are much more sophisticated and subtle than an economic "pass-through mechanism".

Similarly, it is generally conceded that the relationships among global, national and subnational scales change as the international system changes. So, the rules for producing, consuming, and trading commodities change with the advent of global shipping in the 1870s, and the onset of the Great Depression. In fact, the scalar issue revolves in part around the division between discussions of "appropriate scale" (i.e., the strategy of addressing scales without crossing them), versus the comple-mentary need to analyse the relationships between scales at different times in society and nature. The "appropriate scale" concern would suggest deriving a function for mapping local to national to global linkages, or partitioning the data more coarsely and applying local equations to the data, or recalibrating the local equations to coarser data. The cross-scale concern is explicitly empirical and focused on tracking influences across scales of organisation through historical time, allowing for - and even emphasising - system shifts across spatial and temporal scales.

Issues of Classification and Data

Classification

The study of land-use/cover change requires either standardised classification (or typologies) of use and cover and/or data provided in a manner that allows various standardised sets of classifications to be constructed. Methods of defining land in terms of climate, topography, soils, vegetation, or productive purpose have a long history. Yet there is no satisfactory and commonly accepted method of defining and classifying land use globally, let alone a definition of the major classes of land use as such (Duckham and Masefield 1970; Evenson et al. 1970; Kostrowicki 1984). This situation, of course, thwarts the systematic collection of data pertinent to use classification. The situation is much better for land cover, where global databases exist, although, again, no agreed set of principles is applied worldwide (for a review, see Leemans et al. 1995).

Land use lacks a common terminology and unit of analysis, a problem that long plagued soil and vegetation classifications. In some cases, no distinction is made between use and cover; in others, use is considered purely as the socio-economic side ("what people do ") of biological cover ("what you see "). It must be recognised, however, that land use ("what people do ") also has a biophysical side that is not identical to cover and is not captured in classifications that follow from that emphasis alone (Fig. 3). In short, the land-use/cover community requires classifications that meet several research needs and, therefore, involve different data.

Land-Use/Cover and Classification Dimensions

The community's varied needs suggests that land-use/cover classification should involve at least three dimensions. The first dimension involves the concrete manipulation of land characteristics: "how the land and cover are used", as in the slash-and-burn sequence of cutting, drying, burning, planting, weeding, and harvesting. These manipulations are biophysical in nature and are not always easy to detect. They can range from strategies that protect an ecosystem (e.g., wildlife preserves) to minor appropriation of photosynthetic products in which most of the ecosystem structure and functions are left intact (e.g., culling trees among some forest gatherers or grassland burning among some pastoral groups) to the creation of an artificial or semi-artificial system bearing little resemblance to the ecosystem that would exist without human presence (e.g., drainage of wetlands). These manipu-lations can only be determined over their full sequence or time period. A framework already exists to describe land use through the operation sequence concept (Stomph and Fresco 1991; Stomph et al. 1993), which involves the relevant features relating to energy, nutrients, water, implements, and the timing of applications. Finally, the unit of analysis in this biophysical meaning of land-use is a geographical one, referring to the field, plot, or part of the land surface in question.

The second dimension refers to the land user's purposes or objectives served by the manipulation: "why the land is used". These objectives may vary considerably among individuals, societies, and historical periods, but generally include the satisfaction of needs for income, food, feed, fuel, pharmaceutical products, shelter, and landscape values. This dimension should not be confused with biophysical land use and cover. The same need for, say, 200 kg of rice per ha may be satisfied through very different land uses and covers, ranging from long-fallow shifting cultivation with average yields of less than 1,000 kg/ha to irrigated triple-crop rice production with annual yields of up to 10 t/ha. The purpose/objectives dimension is important, however, to distinguish such critical attributes as subsistence versus market orientations, which usually respond differently to changing conditions. This dimension of land use and cover nearly always operates at the level of the farm or management unit; it relates, therefore, to a socio-economic unit.

Few classifications of purposes/objectives have been developed and applied globally, although location-specific studies exist from which some universal descriptors may be drawn. Typologies are far more prevalent here than classification (v. Turner and Brush 1987). If this dimension is to be incorporated into a classification, suitable descriptors (i.e., purpose equivalent of the biophysical operation sequence [above]) must be found. The unit of analysis (parcel, farm, farming system, household) also needs to be defined. Classification of land users is probably the easiest route to a purpose-oriented classification. It is noteworthy that the objectives of land use are not necessarily coincident with biophysical manipulation.

The third dimension of use is the broader biophysical and socio-economic circum-stances or underlying conditions. Biophysical conditions - for example, climatic zone, soils, occurrence of pests and diseases - determine in part what type of land use and cover may be found. Bananas cannot be grown in Scandinavia outside greenhouses, and rubber in Central America cannot be grown because of disease pressures, although the climate is suitable. Detailed world databases on biophysical resources (e.g., topo-graphy, soils, climate) and a global agreement on what constitutes important descriptors will permit the classification of these broader biophysical conditions.

What land use and cover is chosen within the boundaries they set is a function of the socio-economic and technological circumstances, such as demographic factors, marketing, and infrastructure systems, and land tenure arrangements - commonly referred to as socio-economic land-use drivers. Even within a homogeneous agroclimatic and socio-economic region, however, individual farming units differ in land use and land cover.

Major classification efforts aimed only at the broader circumstances of land use and cover are unnecessary nowadays because of data storage and processing technology (Anderson et al. 1976; Vink 1975). New databases from remote sensing will allow individuals to build different typologies for their specific needs. However, there is considerable merit in disentangling the broader biophysical and socio-economic circumstances from land use and cover sensu stricto, as in the FAO/UNESCO soil classification (1974, 1991; also FAO 1993c).

LUCC research should emphasise the development of classifications and data on the three dimensions noted. Global classifications combining these dimensions into land-use systems have proven difficult to achieve, in part because the kinds useful for national purposes may not be so for international comparative research. Of course, having the three dimensions should allow the construction of the specific classification for local-level analysis (Fresco and Westphal 1988; Gils et al. 1991).

Previous Attempts at Land-Use/Cover Classification

Land-use/cover classifications, which can be traced back to early civilisations, were almost always based on field surveys until the middle of this century. In the late 1960s, however, such surveys declined because of their costliness compared to new survey techniques based on computer processing of aerial photographs and satellite images. These technologies directed classifications towards the land-cover attributes captured in such imagery. In fact, many existing land-use classifications are based on the vegetational and artificial cover of the land surface: the World Land Use Classi-fication, The Canada Land Inventory and Land Use Classification, the Second Land Use Survey of Britain Classification, the Canadian Land Use Classification, and the World Map of Present-Day Landscapes (Moscow State University-UNEP 1993; Rjabehakov nd.), to name a few.

World-wide classifications based on cover alone are insufficient for the use dimensions noted above; a few attempts to include these other dimensions exist (v. Kostrowicki 1983).

A recent review (MŸcher et al. 1993) indicates that none of the many "land-use" classifications is acceptable or satisfactory in a global change context. All reviewed classifications suffer from one or more of the following drawbacks:

(i) The lack of a sound definition of the units of analysis, ranging from field to farm to region (confused with mapping units)

(ii) Overlapping land-use classes (because of the lack of clearly defined criteria; most hierarchical classifications are only comprehensive at the first level, and are far from comprehensive at lower levels)

(iii) The near-total absence of quantitative class boundaries (critical or threshold values of the criteria), adding a significant subjective element to land-use assignments

(iv) The combination of land use with other dimensions, such as climate characteristics, that may influence land use but are not inherent features of it

(v) The multiplicity of land-use classification objectives, often closely tied to regional or disciplinary foci.

Past attempts at classifying land use and cover are either not global in character or not sufficiently comprehensive. Furthermore, existing classifications do not use common classificatory principles and often conflate use and cover. Recently, several inter-national agencies, including FAO and UNEP, have initiated a discussion on the subject of land-use/cover classification and databases and have commissioned preparatory studies for the purpose of rectifying the situation.

Data

Only a few datasets on land-use/cover change exist that are readily adaptable for LUCC now - that is, spatially comprehensive and sufficiently accurate (e.g., Flint and Richards 1991). There are three areas of uncertainty that need much better documentation and analysis: (i) the state (e.g., information on biomass, net primary production, etc.) and distribution of existing land cover, (ii) the rate and distribution of land-cover con-version, both historically and currently, and (iii) the underlying factors which describe land-use and land-management practices. Clearly, some combination of historical reconstruction and remote sensing is needed to refine the first two areas. The third area of uncertainty will require closer linkages of physical and social analysis.

Coarse resolution remote sensing data could provide the basis for defining the distribution of current land cover. The advantages these data have over existing maps are temporal consistency and an explicit definition of actual, rather than estimated, boundaries between cover types. The most straightforward approach would be to derive maps of current land-cover types from remote sensing measurements along pre-defined classification systems. It seems unlikely that a single classification will suit all needs, but much could be gained by initiating international efforts to collect the necessary datasets from existing satellite sensors (such as AVHRR) from which various classifications could be made on a case-by-case basis. A remote sensing-based map of current land cover could form the basis of a pre-disturbance land-cover map, created by correlating existing natural land cover with physical variables (e.g., temperature, precipitation, edaphic conditions), or through approximation based on simple assumptions of contiguity and spatial clustering. With such maps of both current and pre-disturbance land cover, it might be possible to reconstruct the history of land-cover change with the addition of geographically-referenced time series of human use and conversion, such as maps of the expansion of deforestation. Since much of the analysis is spatial, a geographic information system (GIS) would be used to organise the data and analysis.

One of the most important land-cover changes is the conversion of temperate and tropical forests. The use of coarse resolution remotely sensed data (1 km or greater) to map land-cover conversion has frequently been considered the optimal approach for monitoring land-cover change since it requires fewer data than do high resolution sensors (less than 100 m). However, when coarse resolution datasets have been used in the past, they have tended to overestimate deforestation. This overestimation bias is partly related to the geometry of clearing, so a single conversion factor cannot readily be developed. Considerable work remains to be done before mixture modelling, and other techniques which could derive an accurate estimate from coarse sensors, can be used. Meanwhile, the best approach appears to be one based on high-resolution data from such satellite systems as Landsat.

While high resolution satellite data are improving measurements of deforestation, the dynamics of clearing, abandonment, regrowth and re-clearing are completely unknown, yet could be important to analyses of the net flux of carbon. In addition to quantifying deforestation, the use of high resolution data provides detailed infor-mation on regrowth and abandonment. More difficult still is the monitoring of changes in non-forest vegetation. High resolution satellite data will be invaluable sources for measuring these changes but considerable methodological work remains to be done.

Documentation of land-cover change is only the first step toward understanding the underlying agents of the change. Systematic and sub-national data on land-use management, including the operational sequences and techno-managerial inputs, are required. Likewise, systematic and sub-national data on a range of socio-economic and demographic variables are needed. Tenurial arrangements, informal market data, population growth rates, levels of subsistence and market production, and other such complex data are examples. Such data may prove very difficult to collect; much care should be taken in formulating research approaches (see Section 8).

Policy Relevance of LUCC Research Programme

The human driving forces of land-use/cover change are the primary foci of LUCC, set within the biophysical parameters of land cover. LUCC offers the scientific research and policy communities a global-to-local (and local-to-global) basis for analysing how land cover is converted, what kinds of land uses and covers result, the local, regional, and global environmental effects of those results, and the likely points where human communities can intervene to change the trajectories of global land use according to changing needs and values.

In short, then, LUCC proposes to provide a broadly augmented, scientifically rigorous and dynamic information base that can inform the policy process at the local, national, and transnational levels. Specifically, it can provide information relevant to land-use, resource, and environmental policy and planning, including the human responses to environmental change and the sustainability of rural activities. LUCC cannot, in the absence of a clearly stipulated set of policy values and institutional settings, offer policy prescriptions. Nor should it aspire to do so. But it can provide science advisors and policymakers with: (i) the informational backdrop for improved policy (within a given policy framework); (ii) the databases for scenario analysis and improved adaptive management systems; improved pathways to integrated assessment and observation; and, (iii) a long-range set of scientific goals to assist in setting future policy priorities within the complex of global environmental change as it occurs and our understanding of it grows.

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4. Structure of the LUCC Plan and Links to Other IGBP and HDP Activities

A LUCC programme that serves the wide-ranging needs of the global change community requires an approach that is broad in its implications but specific in its content and immediate objectives. LUCC received its mandate from both IGBP and HDP because of the recognition that land-cover change was a crucial component of global change and that its dynamics could only be understood through an integrated science research agenda incorporating nature and social science approaches. Such a mandate requires the engagement of a broad range of perspectives and approaches (Turner 1991). It also demands focus on some specific science goals, through which other IGBP and HDP projects and activities link into the LUCC agenda. Appropriate balance among these needs is best achieved by identifying the major science questions of LUCC and linking those questions to specific research outputs (research foci).

Significant improvement in understanding land-use/cover change for the range of users in the global-change arena would follow from improved resolution of these five major question:

1. How has land cover been changed by human use over the last 300 years?

2. What are the major human causes of land-use change in different geographical and historical contexts?

3. How will changes in land use affect land cover in the next 50-100 years?

4. How do immediate human and biophysical dynamics affect the sustainability of specific types of land uses?

5. How might changes in climate and global biogeochemistry affect both land use and land cover, and vice versa?

Because the study and analysis of research addressed by LUCC covers a new interdisciplinary area, and because it is recognised that considerable integration of LUCC research with that of other Core Projects will be necessary, these goals will only be met through close collaboration with other Core Projects.

Investigating these questions requires research progress towards the following goals:

A. (Question 1 and 5) Improvement of the data and data-based estimates for the major land covers and the changes in these covers for the last 300 years, with increasing spatial and temporal resolution for last 100 and 50 years, respectively.

B. (Questions 1 and 3-5) Determination of the spatial scale and pace of changes in the major land uses and covers, including cover conversion and modification. C. (Questions 2-5) Empirical identification of the major driving forces (exogenous variables) of land-use change as they relate to the land manager and use-system for critical land covers.

D. (Questions 2-5) Empirical identification of the major kinds of land-use/cover change dynamics operating throughout the world.

E. (Questions 1 and 3-5) Refinement and development of new suites of geographically explicit land-use/cover models using both empirical-based diagnostic and behavioural-based regional approaches.

F. (Questions 3-5) Refinement and development of new suites of prognostic land/use models capable of incorporating biophysical and climate impacts.

G. (Questions 3-5) Determination of the sensitivity of such models for use in assessing future scenarios of land-use/cover drivers and conditions.

The major questions may be addressed through a range of approaches, some of which may require assessments of competing theoretical models, whereas others may well invite empirical examinations, without explicit recourse to formal theoretical constructs. Both modes of analysis have proven useful.

The IGBP-HDP LUCC research project/programme, therefore, seeks to improve under-standing of land-use/cover change while maintaining an openness to the varied and competing community of approaches to the problem. It does so through a science/ research plan that integrates empirical and comparative research with modelling through three research foci and two integrating activities (Fig. 11):

Focus 1: Land-Use Dynamics - Comparative Case Study Analysis
Focus 2: Land-Cover Dynamics - Direct Observation and Diagnostic Models
Focus 3: Regional and Global Models - Framework for Integrative Assessments
Integrating Activity 1: Data and Classification
Integrating Activity 2: Scalar Dynamics

Research Foci

Focus 1 is a case-study approach to understanding the dynamics of land use and cover by kind or class of situation (use/cover context). It is constructed on the premise that a large measure of understanding these dynamics is gained from the perspective of the land manager (i.e., farmer, forester) who is the agent of direct change in land use and cover, responding to the events and processes that impinge upon this use. Focus 1, therefore, aims to identify the major kinds of land managers and the dynamics in which they are engaged (Question 2) but in so doing, engages the kinds of use/cover changes that have taken place in the past (Question 1) (Table 2). Focus 1 will plan and carry out comparative case studies of land-use/cover dynamics using common protocols and standardised terms and measures of land use and its dynamics; analyse the results to identify and demarcate spatial situations of land-use/cover dynamics, and improve understanding of the intricacies of these dynamics, stating the generalities that can be gleaned about them; and build from these cases and analyses to local to regional explanatory models of land-use/cover change. Focus 1, therefore, draws the specificities and generalities of regional situations of land-use/cover change for incorporation into Foci 2 and 3, making regional and global models more sensitive to the great variations in LUCC. It provides land-cover transition probabilities to Focus 2 and the local to regional specificities of the human and biophysical forces of change to Focus 3.

Focus 2 incorporates direct observations into spatially explicit empirical models of land-cover change processes. The emphasis of this Focus is to capture the dynamics of land conversion and modification for key regional issues, such as conversion of tropical forests, degradation of savanna systems, and the like. It accomplishes these through the use of remotely sensed imagery of land-cover change to capture the spatial range and pace of cover change, and combines the results with case study information on land-use dynamics through diagnostic models that can be used to understand the process of cover change and make credible near-term projections. As such, Focus 2 address questions 1, 2, and 3 (Table 2). Focus 2 activities contribute to Focus 1 by facilitating the coupling of site-specific use dynamics with large-scale regional changes in land cover, while they provide the spatial patterns of these changes to Focus 3, allowing more aggregated analyses to have an explicit spatial component.

Focus 3 develops various structures for new and improved behavioural models of land-use/cover from the regional to global scale. These models will be used to provide projections of land-use/cover change (Question 3) and, in turn, provide a means for assessing the impacts of environmental changes on land use (Question 4) (Table 2). Models of the kind sought in Focus 3 must be dynamic and geographically explicit and involve the major socio-economic and biophysical driving forces of land-use/cover change together with biophysical feedbacks to those forces and to global change.

Such models aim to provide projections of land-use/cover change and associated biophysical parameters, including vegetation attributes and resource accumulation and degradation, for periods of 50-100 years and a spatial resolution of 10 km2 to 50 km2. Thus, the models must also be adaptive in the sense that tastes and values of society(ies) change and are likely to do so over the time periods investigated here. Finally, Focus 3 will perform model validation and sensitivity analysis. This focus provides the boundary conditions and temporal dynamics needed for Focus 2 and the exogenous or international influences on the case studies in Focus 1.

Integrating Activities

Cross-cutting the three foci are two important activities - information and conceptual issues central to the research objectives of LUCC as whole, but not grounded specifically within any focus (Fig. 11). The first activity is data and classification related to land use and cover and is particularly important for Questions 1 and 2 (Table 2). Other IGBP and HDP projects/programmes and other agency activities have been charged to develop and maintain datasets on land cover, land use, and socio-economic variables related to both. These efforts, however, will not necessarily generate these data in forms useful to LUCC, unless the LUCC requirements are identified and translated to those projects and agencies. The data and classification activity does this by providing a rationale for the kinds of data needed and how they can be combined to create the variety of classifications and typologies that will, no doubt, be used in forthcoming LUCC-related work.

The second activity - scalar dynamics - addresses the differences in land-use/cover dynamics at different spatial, temporal, and hierarchical levels of analysis of operation. It aims to cull from the knowledge gained in the activities of the three foci, as well as from other related efforts, the general lessons about the nature of these dynamics as they are observed at different scales and levels of analysis, including the identification of heretofore neglected variables, their influence and distribution. These lessons are central for systematic understanding the flow of processes through different scales, contributing to Questions 2, 3, and 4 (Table 2).

Linkages between LUCC and other Research Projects

LUCC maintains strong linkages with various international research activities and programmes (Fig. 2). As a member of the IGBP and HDP, however, particular attention is given to LUCCÕs linkages with the other projects and activities within the auspices of these two programmes.

The IGBP studies the physical, chemical, and biological processes that regulate the earth system, and the manner in which these are influenced by human activities. Most IGBP core projects can provide LUCC with an enhanced understanding of the biophysical driving forces that influence the potential range of land uses. LUCC can provide the other core projects with projections of changes in land cover and knowledge based on the processes involved in land-cover change. Besides these overarching interactions, most cover projects need specific contributions from, and can contribute to, LUCC research (IGBP 1994).

GCTE (Global Change and Terrestrial Ecosystems) aims to define the contributions, responses, and feedbacks of terrestrial ecosystems and agrosystems to global change. This research on biogeochemical cycles, vegetation dynamics, and agricultural yield response is of direct importance to LUCC because it defines to a large extent the biophysical driving forces needed to define land-use potential. The LUCC research on scalar dynamics should be compatible with GCTEÕs research on defining these driving forces across local and regional scales. LUCC could provide an analysis of land use on the GCTE transects studies, which then could become an important benchmark for integrated IGBP research.

BAHC (Biospheric Aspects of the Hydrological Cycle) aims to understand and model the biospheric processes that control the hydrological cycle. Land cover is an important determinant of these processes, and BAHC, therefore, can draw heavily on the outcomes of LUCC research. BAHC has developed a strong focus on biophysical scaling dynamics on which LUCC should draw. BAHC further develops with DIS a set of advanced databases that LUCC can utilise.

LOICZ (Land-Ocean Interactions in the Coastal Zone) seeks to understand how changes in processes in coastal zones affect global change. Coastal land use and cover may be affected by sea levels and may involve other phenomena such as sea defense, construction and groundwater use; and, a large proportion of humans live within, and transform, the coastal zones. For these reasons, LUCC needs to work closely with LOICZ. It can provide LOICZ with the driving forces of coastal land use/cover and, in turn, receive information about the impacts of sea-level changes on land use.

PAGES (Past Global Changes) aims to understand past change in vegetation and sea levels at high levels of spatial and temporal resolution. Together with LOICZ, a focus has been developed on the historic changes of coastal zones. Land use is considered and the historic activities of LUCC should link to those in PAGES where possible. The use of historical data on land use and land cover to calibrate LUCC models and the use of LUCC models to simulate landscape change should provide insights on which PAGES can draw.

IGAC (International Global Atmospheric Chemistry) addresses the processes that determine the chemical composition of the atmosphere. Greenhouse gas fluxes from the biosphere and land use are of importance for such understanding. IGAC developed a comprehensive database on land- use related emissions, such as biomass burning and rice paddies. For future projections of greenhouse gas emissions and fluxes, IGAC is dependent on a firm understanding of land cover and use, which LUCC should provide. In addition, LUCC complements well the emerging effort in IGAC to examine the interactions between trace gases emitted by metro-agroplexes and their impacts on socio-economic activity in those same places.

GAIM (Global Analysis, Interpretation, and Modelling), a task force among projects, involves developing, interpreting, and applying comprehensive prognostic models of the global biogeochemical system and linking them to the climate system on different spatial and temporal scales. LUCC should provide GAIM with model capabilities of a wide range of land-cover changes under various socio-economic conditions, while GAIM could assist in defining scalar dynamics appropriate for LUCC.

IGBP-DIS (Data and Information System) develops improvements in the supply and management of data and information. It is important to LUCC in respect to data harmonisation and standardisation, and could provide a link between data collecting organisations and LUCC researchers.

HDP advances research on topics that are critical for understanding both the human role in global change and the implications of global change for society (Jacobson and Price 1991; HDP Work Plan 1994-1995). It has identified six areas of human behaviour that have particular relevance for global change research. Land-Use and -Cover Change is one of these themes, but all of them are interrelated as each addresses parti-cular aspects of social systems and processes that affect or are affected by changes in the physical environment. To build cumulative understanding of the human dimensions of global change, each research theme will provide input to the others and receive output from them. Some of the relevant linkages are presented below.

Research within the context of "Industrial Transformation and Energy Use" addresses the spatial and temporal changes in the production system in order to evaluate their impact on the environment. It studies the different patterns of industrialisation, different regulatory systems, and material and energy flows associated with different production systems. It will model energy production and consumption, attempt to develop trajectories of future energy use, and assess the cost and effectiveness of various policies enacted to influence energy consumption. LUCC can provide this research programme with data on the evolution of land-use patterns in relation to industrialisation and in the context of urban-rural dynamics. Understanding the demand functions in these dynamics is essential for LUCC models because they affect land managers and their decisions about land use. Energy models provide another means of assessing potential impacts on land management decisions.

LUCC is also closely tied to the research programme on "Demographic and Social Dimensions of Resource Use." Indeed, part of the goal of this latter focus is to synthesise the findings of the other research areas to develop models of interaction between population and resources. LUCC addresses this goal in its emphasis on land as a fundamental resource and the role of population and institutions on its manage-ment. Thus LUCC will provide the data on the associations of land-use/cover change with different population and institutional dynamics, such as rates of growth and property rights. The "Demographic and Social Dimensions" focus links these issues more broadly to general resource and policy questions, and thus can inform LUCC of them as they act as exogenous influence on land management. Because water, unlike energy and land, is not the focus of a particular research programme within HDP, "Demographic and Social Dimensions" will pay particular attention to water issues within these interactions. Moreover, it can provide understanding of distributional issues, both through time and across space. It will develop models to describe population evolution, including migration, as it relates to exchanges and transactions such as trade and financial flows.

Understanding human perceptions, assessments, knowledge, and attitudes is essential to explaining why people act in particular ways and to assess whether policy devised to modify behaviour will be accepted within specific contexts. Research within the theme "Public Attitudes, Perception, Behaviour, and Knowledge" can potentially provide information to LUCC on, for example, native classifications of land resources, evolution of tastes, or attitudes and perceptions about policy and regulation of land use. Diagnostics of land cover and land use will be essential to attitude surveys to assess the relation between attitude and behaviour. LUCC can also provide details about the validity of the proclaimed and actual actions of land-mangers.

Many of the factors influencing land use and therefore land cover are related to institutional arrangements determining property systems, land management, and land reform. LUCC will describe the variety of these within different social systems and analyse their impact on land use and land cover. The "Institutions" theme will inform LUCC of the role of international treaties and government regulations on land-use dynamics and their effects on rules of access and use that will in turn shape the dynamics of land use and land cover.

To be able to respond and adapt to changes in the land base caused by environmental change requires understanding of the mechanisms that influence land use through time and across space. In the context of developing mitigation strategies and designing incentives and constraints to facilitate appropriate response to rapid change or to preserve the land base for the future, LUCC can provide the research programme on "Environmental Security and Sustainable Development" with diagnostics about current land use and cover and its likely change based on improved understanding of land-use dynamics. As such, LUCC provides a basis for identifying a range of security and sustainablility attributes about places. In turn, the "Environmental Security and Sustainable Development" provides LUCC with an understanding of the broader facets of the problem as they impinge on land managers. Together, the two themes will help LUCC to assess the role mitigation strategies in changing land use patterns and will contribute to the identification of communities at particular risk in the face of change.

The HDP is also developing a DIS (Data and Information System) to improve in the supply and management of data and information. As with IGBP-DIS it will be important for LUCC to work with this DIS to identify standard measures and data pertinent to LUCCÕs agenda.

LUCC also contributes to the START (Systems for Analysis, Research and Training; HDP, IGBP, WCRP) effort. The START regional research centres could provide a basis for a globally comprehensive network of case studies linked into land-use/cover issues. Such a emphasis has already been taken by SARCS (Southeast Asian Regional Center for START) in cooperation with members of the CPPC-LUCC, providing a trial for many of the research themes articulated in this report (see Sections 5-7). In addition, the IAI (Inter-American Institute) has been in contact with members of the CPPC-LUCC about a complementary land-use/cover effort in the Americas.

Those programmes concerned with climate impacts and climate research will benefit from information on the sensitivity of land use and land cover to climate change, and on the interactions between land cover and the atmosphere. These programmes includes the WCRP (World Climate Research Programme), WCIRP (World Climate Impacts and Response Programme), and the IPCC (Intergovernmental Panel on Climate Change).

The FAO will be both a major source of data for LUCC and an important user of LUCC-derived projections as a basis for considering the causes and consequences of future agricultural and forestry development. IIASAÕs new initiative on regional modelling of land-use/cover change in mid- to high-latitude Eurasia, which strongly comple-ments the LUCC strategies in this science/research plan, should provide leadership particularly for global and regional prognostic models of LUCC.

Finally, LUCC will complement existing global monitoring programmes such as UNEPÕs GEMS (Global Environment Monitoring System) and GTOS (Global Terrestrial Observation System), which is presently in a planning stage.

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5. Focus 1: Land-Use Dynamics - Comparative Case Study Analysis

Introduction

A comparative case-study analysis of the human dimensions of land-cover and -use change can serve several distinct objectives:

- Link biophysical and human aspects of land cover and use
- Outline a framework for an eventual global catalogue of land-use situations and dynamics
- Link the analysis of human dimensions to global land classification and land-cover modelling efforts
- Take a first step in determining what regions of the world deserve priority in future empirical research on global land-cover and -use change.

Focus 1 has two purposes: (i) to build a firm understanding of the regional dynamics of land-use/cover change through the comparative analysis of land-use change, and (ii) model empirically land-use change situations and dynamics at the subnational and national (local and regional) scales. It addresses the following basic questions:

1. What are the main driving forces and constraints that influence human land managers to maintain or change land use over time?

2. What are the mechanisms and processes by which land managers develop a land-use system, defined in terms of an operation sequence? How are their purposes translated into action?

3. What are the effects on land cover of the application of a land use over time? How do these consequences feed back to land uses and their driving forces?

Aims

(i) To undertake comparative studies of land-use/cover dynamics using common protocols and standardised terms and measures of land use and its dynamics

(ii) To use the results of these studies to identify and map situations of land-use/cover dynamics, and to improve understanding of these dynamics, gleaning generalities from these studies

(iii) To build, from this analysis, local and regional models of land-use/cover change.

Activities

The activities of Focus 1 (Fig. 12), as they are linked to Foci 2 and 3, should lead ultimately to an empirically derived modelling framework that builds on the essence of comparative empirical analysis: the consideration of micro-scale phenomena (where land management takes place) against other phenomena of similar kind and scale, within the ambit of the social system as a whole (Ragin 1981). The Focus 1 modelling framework should interact with Focus 2 empirical thematic assessments and with Focus 3 global modelling efforts, which emphasise global to national scale and macroeconomic phenomena. As a modelling effort, Focus 1 should not pretend to exhaust the full range of land-use practices or locales; it should concentrate on areas of priority to other IGBP and HDP projects/programmes and to global environmental change.

Focus 1 activities also include an effort to determine the scales at which important social forces such as politics and policy, cultural practices, different forms of social organisation on the land, and so on, are most important to land-use and cover change, and where they are not important at all, or perhaps important only as rate modifiers.

Focus Activity 1.1. Developing a global sampling and study framework

A rich, diverse body of literature on land-use/cover change already exists. This wide range of scholarly knowledge, linked neither to global change per se nor to supra-national modelling perspectives, must be brought to bear on Focus 1 case-study efforts. Proper use of this literature and its various methodological approaches can accelerate Focus 1 efforts to select research sites from the universe of possibilities. The first activity of Focus 1 will be to organise and assess this literature with that purpose in mind. It is clear, however, that sites and study teams must be chosen according to an explicit set of criteria, including the availability of qualified interdisciplinary research experts in both biophysical and social dimensions; fit with the highest priority land-use modalities identified; geographic location; theoretical significance; and so forth.

This activity must consider judiciously the extensive literature on land-use change, which is too large and diffuse to review in its entirety. Selection should be guided by the quantity and quality of relevant work on particular areas and by the centrality of the areas to the issues addressed in LUCC. The latter consideration requires the identi-fication of land-use/cover change areas and dynamics of greatest interest. From the areas so identified a number should be chosen based on the availability of data and researchers as well as linkages with studies in Foci 2 and 3. The size of the areas to be examined will, of course, vary, but would normally be larger than the land unit, smaller than the nation (with some possible exceptions), and roughly equivalent to the ecological notion of landscape (Bailey 1983; Klijn and de Haes 1994). These areas should also be catalogued according to their land-use/cover situations (or modalities) and bounded in space. The cataloguing effort should expand on other such typologies (Tiryakian 1968; Weber 1949) by including dynamic and historical elements of change through evolving sets of drivers and outcomes. A situational catalogue will influence the level of spatial disaggregation and, hence, the spatial specificity of global LUCC models. In the end, however, it may be as interesting for its identification of outlying areas, or the areas in which the situations are not or are only marginally applicable.

To be comparable, the studies require a common protocol to guide regional analyses and retrospectively organise existing literature Such a protocol should identify aggregate data relevant to the HDP-DIS and IGBP-DIS efforts, methods of analysis appropriate to the principal hypothesised social and biophysical driving forces, and agreement on the terms used to classify land use and the modalities of use/cover dynamics. This protocol is intended not to restrict the research, but to set a minimum standard for comparability and approach. Complementing the protocol should be a set of methods and field strategies that will enable natural and social science analysts to address linked questions: methods and strategies that should be periodically evaluated.

Focus Activity 1.2. Identification, description, and qualitative modelling of the role of key driving forces of land-use maintenance and change

This activity, anchored in site studies, should be seen as an empirically-driven land-use modelling effort informing empirical assessments of land-cover change (Focus 2) and making global models more robust and regionally sensitive (Focus 3). It aims to improve understanding of biophysical and human processes and activities that maintain or change land use. Where human driving forces are weak, land cover is determined by biophysical energy flows and the state characteristics that these forces influence. Biophysical variables generally constrain land use at most of the time scales over which land use changes, as recognised in various models of land-use potential, such as crop suitability models and the FAO's agro-ecological zones (Rosenzweig 1993; Turner and Benjamin 1994). These constraints can change over time, sometimes quite rapidly, and events that over a long period are quite normal can come as surprises because of their episodic nature. The biophysical world is also a source of driving forces that at times can change the path and state of land use. Natural dynamic cycles of disturbance both influence human use and determine the ways in which human disturbance will affect the system (Uhl et al. 1990). Examples include fire cycles, pest outbreaks, the El Ni–o Southern Oscillation, and ecological succession (Holling 1992). Phenology and successional pathways on natural and anthropogenically disturbed land also determine the consequence of human intervention and constrain future land-use possibilities. Multiple equilibria in land cover are possible, even in the long term, meaning that the timing and character of intervention determine successional outcomes (Holling 1973; Foster 1992).

The salience of socio-economic and political driving forces determines the paths of land-use change, the propensities for certain operation sequences, the time scale over which systems are in apparent equilibrium, and the susceptibility of use/cover situations to external or internal human-induced change. The range of possible drivers, the prevalence of certain kinds of drivers over others, and the importance of outlying cases must be identified and linked across scales. In addition, landesque capital (long-term inputs for land improvement, such as terraces) and infrastructure (e.g., transportation networks) should be considered. On scales ranging from fields to farms and sometimes up to communities, their effects resemble those of biophysical driving forces, in that they alter the biophysical constraints on land use. On scales from communities through regions and up to nations, they are more closely related to social driving forces. The development of landesque capital has two kinds of effects on land cover: (i) direct effects through the physical manipulation of the environment, including habitat fragmentation and disruption of hydrology by road building, reclamation of wetlands, and reservoir clearing and filling; and (ii) indirect effects on cover through effects on other land uses, giving rise to decreased factor costs in agriculture, increased market access, dampening of oscillations in water supply, catalysis of immigration initially for construction and later for settlement, and so forth. The sum of indirect effects is often much larger than the direct effects on cover.

Finally, the driving forces of change must be considered over the course of a systemÕs development, permitting analysis of historical change as an exogenous variable. It may be, for example, that one of the greatest period shifts in 20th century history, the Great Crash and onset of the Great Depression, did not produce a commensurate shift in land-use patterns at the local scale in many cases (e.g., subsistence maize cultivation in the Andes), but did produce such change in others (e.g., cotton production in the southern United States). The impacts on existing systems of shocks of this kind cannot be adequately understood without tracing the historical context in which they occur. Such observations on the differential impact of macrohistorical change reveal the susceptibility of local land-use systems to exogenous change and suggest some limits to rational economic models imputing homogeneous impacts. Similarly, adding a historical dimension avoids the problems of trapping the modelling exercise within a specific historical conjuncture or mode of production. Failure to do so has led land-use analysts to conclude, for example, that swidden disappears in the presence of perma-nent agriculture or agricultural modernisation, when the literature demonstrates its persistence as a land-use type across broad historical time (Dove 1988; Richards 1985).

Focus Activity 1.3. Assessing the dynamics of change and stability in systems of land use

As noted in IGBP Report No. 24/HDP Report No. 5, land-use/cover dynamics involve an intricate set of relationships among the land user, the larger socio-economic setting, the land in question, and biophysical feedbacks to the use employed. Local and regional models must be grounded in a firm understanding of these relationships, involving several attributes.

(i) Lands are managed differently by different classes of human agents. For example, the simplest categories of distinction between agricultural producers may be between those who are consumption-oriented (for subsistence, or to trade for the means of subsistence), commodity-oriented (for profit), or somewhere in between (Kates, Hyden and Turner 1993; also Brush and Turner 1987). Agents also differ in such attributes as temporal and spatial scale of production, intensity, inte-gration into non-local market processes, adaptations and attitudes toward risk, demographic and tenurial characteristics (Popkin 1979).

(ii) The second attribute is the land-use practices that influence land cover. The proximate anthropogenic determinants of land cover can be usefully portrayed using the concept of an operation sequence (Stomph and Fresco 1991), defined for agricultural use but expandable to include other human uses (see part 3 above). Because an operation sequence occurs over time, and because its effects on land cover depend on temporal interactions between human and natural driving forces, the description of its temporal characteristics is vital. Similarly, the spatial characteristics of an operation sequence influence its impact on the landscape. Ideally, the operation sequences should be georeferenced. The technology must be specified in a way that includes factors of production, capital equipment, and technique. Finally, the operation sequences must be evaluated in terms of their stability and sensitivity to change. (iii) Third are the key sets of driving variables and endogenous dynamics (by class of human agent [i]) that govern the choices of land use. The driving variables or forces will vary by situation, of course, but it is important that a wide range be explored and/or the data collected in a way that their exploration is feasible (e.g. Ostrom 1990). These variables should be qualitatively or topologically modelled to summarise relationships in the form of pattern models (Wilber and Harrison 1978), circuit diagrams (Odum 1983), or fuzzy cognitive maps (Kosko 1986). Such models serve the purposes of stimulating discussion, revealing hidden issues and theoretical biases, and generalising the findings and intuitions of case-based researchers. If made spatially explicit, these models can be extended to serve the modelling functions of Foci 2 and 3.

Focus Activity 1.4. Analysing land-cover consequences

The LUCC project/programme will aid other core projects and research efforts by specifying the land-cover consequences resulting from land use and its driving forces. The relation of land-cover change to other regional and global environmental changes is investigated in LUCC only inasmuch as it feeds back on land management systems. Land-use effects on land-cover change and on ecosystem structure and function on scales from the patch to region are also investigated in GCTE, and these tasks must, therefore, be collaborative.

Land cover is the result of the interaction of human land-use operations with natural biophysical conditions, including the past history of the site itself. The same operation on similar sites may have different results for cover if such factors as seasonal and longer-term fluctuations in rainfall amount and intensity, seedbank and seed rain of successional species, pest cycles, soil condition, and context within different operation sequences differ between sites. The challenge for comparative land-use analysis is to develop generalisations about land-cover consequences not only for individual operations but for their application in sequences, including the role of natural cycles and landscape patterns.

Land-cover change has immediate environmental consequences (e.g., soil nutrient change, habitat fragmentation) that feed back on the land use and on the biophysical and human driving forces. These feedbacks should be examined as they amplify or attenuate land-use dynamics. Actions in the biophysical realm have both intended and unintended consequences for land cover, which generally correspond to positive and negative feedback mechanisms, respectively. An example of a rapid positive feedback is successful crop production, a cover consequence clearly intended by the land manager. Delayed feedbacks also exist, such as soil nutrient exhaustion or improved soil moisture control through incremental irrigation development. Feedbacks can also affect the larger social system, particularly those that engender policy reformulation and reaction, such as forest degradation leading to logging controls leading to local labour adjustments.

It is expected that remotely-sensed data on land cover will be produced and distributed much faster than socio-economic data over the next decade or more. Incentives will exist, therefore, to relate ground-based data to characteristic signatures and changes in remotely-sensed data, with an eye to working backwards from land-cover information to reconstruct likely land-use situations. Such an effort will necessarily involve careful comparison over time with paired remote-ground information from biophysically similar control sites. As relations between process and pattern become tentatively established, they may allow LUCC models developed in both Foci 1 and 2 to be extended to areas where socio-economic data are unavailable, sparse, or suspect.

Focus Activity 1.5. Theoretical work: Model building and prediction

The activities above will provide detailed and comparative understanding on which to construct local to regional land-use/cover change models unencumbered by the biases and assumptions built into existing larger-scale models. This case-study-driven approach to modelling can enrich the global models, by making them more robust and regionally sensitive, if a series of important steps can be taken.

(i) The sampling effort outlined in Activity 1.3 must be extended and elaborated into a true typology of regional situations, with the categories corresponding not to ideal but to real or nominal types (Diesing 1971) of cases with common characteristics and dynamics. Such a typology can be used as a guide in further consideration of cases, or it can be used as a classification system at the regional level to feed into larger-scale modelling efforts.

(ii) The LUCC dynamics identified by types through case studies must be aggregated and/or extrapolated, either case raising a number of cross-scale linkage issues (also referred to as the micro-macro issue; see Section 9). For LUCC modelling in a mechanistic context, at least three types of aggregation methods should be investigated (Rastetter et al. 1992), using: a statistical expectation operator based on fine-scale data and model behaviour to derive larger-scale functional forms (with the attendant risk of analytic intractability); a spatial partitioning and simple linear scaling of small-scale model relations (with the cost of computational complexity); and, large-scale calibration to relate aggregate data (with the risk of spurious correlation: Przeworski and Teune 1970).

(iii) Although methodologically distinct, Foci 1, 2, and 3 should be integrated in multiple ways through model-building, data sharing, and verification. As models are generalised and scaled up to a subnational (regional) level, they will provide a basis for the large-scale macro-modelling exercise. In some areas of the world and for some processes that display loose vertical coupling, they may provide a justification and verification for simpler, less mechanistic models based mostly on large-scale socio-economic parameters. In more problematic areas of the world, and for processes that display stronger vertical coupling across scales, they will provide insight into the level of detail needed for successful prediction and explanation. In all cases they will establish in mechanistic terms the confidence limits and conceptual boundaries for valid models. In many instances, cases will provide estimates of socio-economic parameters and land-cover sensitivities not available on a global extent. In addition, work establishing a typology of situations and their dynamics will provide a basis for appropriate differential application of these parameters across the globe for calibration purposes. Leemans and Zuidema (1995) have noted the problem of linking basically dimensionless socio-economic data with two-dimensional biophysical data. A general typology of situations will help somewhat by reducing the scale and increasing the number of socio-economic regions.

(iv) Focus 1 models will be used to probe the stability regimes and comparative dynamics for land-use/cover situations relative to parameter shifts and over the course of system evolution. It will be essential to investigate the necessary conditions under which land use (and land cover) may be expected to vary continuously and unambiguously, and what sort of prediction is possible over these periods. Where necessary conditions do not prevail, multiple steady states may be identified, and scenario-based prediction may be feasible. Such investigation at the scale of land management may provide confidence limits for predictions on a larger scale.

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6. Focus 2: Land-Cover Dynamics - Direct Observation and Diagnostic Models

Introduction

Although it is an important aspect of global change, our understanding of land-cover change is inadequate for two reasons: (i) we lack accurate measurements of its rate, geographic extent, and spatial pattern, and (ii) we have a very poor capability of modelling from empirical observations. This Focus develops an interdisciplinary approach for analysing land-cover change by coupling empirical observations and diagnostic models.

Direct observations of land-cover change can be made using remote sensing. It is a promising tool for objectively making these measurements at different spatial and temporal scales, from large-scale assessments of regional trends to local-scale analysis of complex dynamics. Additional information can be obtained from tabular census documents. By directly measuring land-cover change, it is possible to explicitly quantify its rate and spatial pattern. This information can be used for specific analysis of land-cover fragmentation as well as for analysis of spatial trends in, and geometric patterns of, land-cover change. Direct observations provide a quantitative assessment of rates of change, which can be used as forcing functions for a variety of biophysical and socio/demographic/economic models. These observations of spatial trends and rates can be used to develop empirical diagnostic models and short-term prognostic models (Lambin 1994).

The synthesis of observations through modelling is central to this Focus. The approach would be to use a combination of region-wide observations, site-specific observations, and case studies to develop models which, although they do not provide functional or process level drivers, can provide credible short-term predictions as well as spatially disaggregated results. Moreover, the results of such observations and models would lend insights into driving variables by highlighting important spatial and temporal occurrences.

Modelling would thus provide a diagnostic capacity of the overall programme to define what is happening in terms of a set of selected important land covers. The importance of this diagnostic modelling for current global change research, such as the imbalance in the global carbon budget, cannot be underestimated. To the extent that such models also provide credible near-term (5 to 10 years) prognostic models for understanding future trends in land-cover change, and hence, climate forcing, they provide a basis for integrating land-cover change transients into terrestrial ecosystem models.

The activities in this Focus would emphasise the following questions:

- What are the rates of land-cover change, and how will they progress?
- Where is land-cover change occurring now, and where will it occur in the future?
- Which spatial and environmental attributes contribute the most to an explanation of land-cover change?

Land-cover change spans many scales of analysis. In the case of deforestation in the Brazilian Amazon region, it has been shown that regional trends are influenced by large-scale external forces but mediated by local-scale conditions (Skole et al. 1994). A multi-level, interdisciplinary approach is therefore necessary. Focus 2 starts with direct measurements of the rate, location, spatial pattern, and temporal characteristics of land-cover change for large regions. At a second level of analysis, site-specific observations could be carried out using multi-temporal, high resolution satellite data to gain insight into local-scale dynamics of land-cover changes. Regional analyses provide information on general trends in land-cover change, while site studies nested in the regional analysis provide insights into fine spatial and temporal dynamics of land-cover transition sequences.

Spatially-explicit observations and empirical models developed in this Focus readily couple to the analyses and models of Focus 1 and Focus 3 (Fig. 13). In one sense, the analyses conducted in this Focus centre on land-cover changes, while the emphasis of Focus 1 is on the relationship between land cover and land use. For instance, site-specific studies in this Focus provide a detailed documentation of patterns, while the case study emphasis of Focus 1 emphasises the underlying causes or processes that lead to the observed patterns. The site studies couple to activities in Focus 1, incorporating survey research and data from census documents to define the parameters that describe the local land-use strategies of the land manager, and how changes in the local environment are brought about by changes in the physical environment that influence the land manager. The work included in this Focus couples to Focus 3 by enhancing the aggregate results with spatial information and detail. One advantage of this linking between direct observations of the land-cover changes with the modelling in Focus 3 is that an explicit treatment of scale and aggregation problems could take place. This Focus also provides an explicit validation of results of more aggregate prognostic models.

The output from Focus 2 provides: (a) diagnostic model results of land-cover changes occurring over the last 20 years and next 10 years; (b) a basis for validation of integrated prognostic models against explicit observations; and (c) the distribution of land-cover change by various cover types. The latter output is significant. Macro-models developed in Focus 3 will be able to predict the increase in cropland area defined through a specified demand function and the availability of existing cropland. Should the model need to bring new land into production, these models will need to define how to partition it between: (a) complete conversion of native vegetation; (b) modification of native vegetation; and (c) re-clearing of successional or fallow vegetation.

Aims

(i) To provide, through direct observations and data, regional and continental patterns of land-cover change needed by the global change research community.

(ii) To provide a basis for analysing the time-varying spatial dynamics of land-cover transitions.

(iii) To develop an empirical and data-rich framework for diagnostic models of current situations and short-term predictions through models based on direct observations.

(iv) To establish a foundation of observations and measurements for spatially disaggregating results from macroeconomic analyses.

Activities

The approach to Focus 2 is shown in Fig. 13. Large-scale observations with high temporal resolution and low spatial resolution data (e.g., AVHRR 1 km data) can provide information on land-cover types and some limited information on land-cover change (e.g., biomass burning).

Regional observations using high spatial and low temporal resolution satellite remote sensing provide data on land-cover change, its spatial geometry, and the temporal sequencing of land-cover change.

Region-wide patterns of land-cover change are the result of many local activities. For example, net deforestation is the sum of several land-cover transitions: primary forest conversion, abandonment of agricultural land to secondary succession, and re-clearing of successional vegetation. These fine spatial and temporal scale dynamics are important, since the pattern and timing of clearing and abandonment affect biogeochemistry and other physical processes. The implications for carbon storage are important, since regrowing vegetation accumulates carbon previously lost to the atmosphere from clearing.

In some land-use systems, especially in the tropics, there is an important relationship between land in active agriculture and secondary growth. The mode of production is predicated upon maintaining both classes of land use. Local ecological conditions, methods of agro-ecosystem resource management, and local-scale decisionmaking are, therefore, important variables in the land-cover conversion process.

It will be necessary to couple large area measurements sampled synoptically every decade or half- decade with a sample-based distribution of site-specific measurements made annually. These site measurements could provide detailed information on the interannual cover-change dynamics. Case studies would become an important component of the work, and links between Focus 1 and this Focus would occur at this nexus.

In addition to regional observations from satellite data, non-satellite information will be very important. Data on land uses, particularly agricultural areas, can frequently be obtained from national censuses. Sociodemographic information can be compiled from censuses and other inventories, or through field activities.

Focus Activity 2.1. Determining important land-cover changes and regions of consideration

The analysis of land-cover change could be a daunting and monumental programme, particularly in terms of the observations required to document land-cover changes exhaustively. Therefore, the first Activity of this Focus is to develop a strategic and conceptual framework for analysis of important regions and time periods. Nominally, the period of the last 20 years is important when geographically distributed atmos-pheric records make integrated global analyses possible. There is, however, a need to develop longer-term historical analyses as well. Regionally, much emphasis is now being placed on the tropical forests, but other areas may become important in the future.

Focus Activity 2.2. Direct measurement of regional and global land cover and land use

There are two major uses for global land-cover stratification. First, such stratification will be used as a framework for geographically mapping in situ measurements to define biophysical attributes for land-use models; and second, as an input to global biosphere models. A rationale for global land-cover stratification for global biosphere models is provided by the IGBP (1992), which also supports the LUCC models. This Focus Activity has direct links to existing efforts to assemble the requisite datasets being coordinated through IGBP-DIS, and should be conducted jointly by LUCC and DIS.

A global land-cover and land-use classification should be emphasised (see Section 8). The classes would be relevant to the needs of the core projects/research programmes and the needs of the modelling proposed in this Focus and Focus 3. The classification could be generated using satellite data and through the integration of existing maps or documents. The integration of non-satellite information would be especially necessary for the development of land-use (as opposed to land-cover) datasets. The emphasis would be placed on developing datasets which provide geographically referenced information on inputs (such as fertilisers), management practices, tenure and other factors related to land use.

There is a need for agreement on the land-cover and land-use classification schemes. Such an agreement is currently being sought by the IGBP-DIS Global Land Cover Working Group. The proposed programme would pursue close involvement with this international activity, and would encourage further development of land-use, as well as land-cover, classification schemes.

The research and development activities needed for this component are primarily methodological. The focus should be on refining the appropriate methodology for multi-temporal, multi-spectral, and multi-year analysis to generate the classification needed for the programme. The appropriate timing needs to be determined for the necessary repeated classification using coarse resolution data. Similarly, tools need to be developed and applied for using coarse resolution data to flag potential areas of change detection. As part of the mid-term development agenda, multi-resolution tools must also be developed for land-cover mapping. In the longer term, procedures need to be established for directly parameterising land-cover characteristics such as biomass and vegetation structure, and to advance them from research demonstration to operational prototyping.

Focus Activity 2.3. Direct observations of land-cover change dynamics

In the last twenty years land-cover change, particularly deforestation in the tropics, has been accelerating as a result of population pressure and economic development. It has been consistently singled out as a key element of many areas of global change research, and is also important to various international policy issues. Yet, in spite of the growing need for precise estimates of rates of land-cover change to support both international policy and basic scientific research, comprehensive and systematic information is not available on a global or regional basis. The latest IPCC report, for example, considers the rate of tropical deforestation to be one of the key unknowns in global climate change assessment. Any lasting and effective implementation of a global emission inventory to support the IPCC process will require a new concerted effort to measure and map tropical deforestation. It is likely that other such land-cover changes will soon be identified as important, for instance the loss of Siberian forest, which may increase in the future.

The concern over land-cover change arises because of its impact on the global environment and its potential influence on climate change. Indeed, some experts believe the direct effects of deforestation or cropland degradation on the environment and human habitability will be even more significant than climate change itself. As noted, land-cover change has historically resulted in as much atmospheric carbon dioxide as fossil fuel burning. If current trends in land-cover change continue, as much carbon dioxide and other trace gases will be put into the atmosphere in the next 75 years as have been put into the atmosphere since 1700.

It is well known that land-cover change is not a unidirectional process (e.g., forests being converted to agriculture). In many parts of the world, abandonment to secondary growth is a significant type of land-cover change. In the Amazon, for instance, this secondary growth amounts to as much as 30% of the deforested land. This important dynamic must be captured in analyses of the land-cover change process since it determines the correct calculation of net emissions. Determining the location and timing of secondary growth is not a simple problem. The mere existence of a large secondary growth pool is not itself an indication of a large carbon sink; consideration must be given to the dynamics associated with this pool.

Recent scientific findings suggest that land-cover change can influence climate change by altering sensible and latent heat flux, planetary albedo, and surface roughness at the planetary boundary layer. More local effects include an increase in soil erosion, an increase in the fraction of precipitation as surface run-off, and an eventual local decline in precipitation. Perhaps the greatest irreversible change associated with land-cover change is the loss of biodiversity from habitat destruction and fragmentation. Some estimates suggest that at current global rates it could result in the loss of up to one half of the world stock of genes, which would dramatically reduce the biological diversity of plant and animal species and severely limit the future of genetic stocks for biotechnology development.

At a national level, numerous reports point to the critical need for reliable land-cover change analyses to support national programmes. For instance, accurate and up-to-date assessments of forest area and rates of depletion are fundamental to the develop-ment of improved national forest management strategies. Moreover, issues such as soil fertility and erosion, water yield, water pollution, and land-use planning are directly linked to land-cover management issues. Two elements are important in this Activity. The first is the development of regional assessments through direct observations, preferably with satellite remote sensing, but using any other suitable means such as aerial photography, census-based mapping, and other cartographic sources. High spatial resolution satellite remote sensing provides a uniform approach to measuring and mapping land-cover change over large areas at fine spatial resolution (100 m), tracking land-cover conversions (and some modifi-cations) at a sub-national level with a high degree of accuracy. This also emphasises rates of secondary succession and the turnover of converted land to regrowth vegetation. This dynamic has important implications for terrestrial ecosystem models as a potentially important carbon sink, as well as forest fragmentation patterns. The latter insight would be useful for extending what we now know concerning the overall impact of land-cover change in forests, and for enhancing with quantitative infor-mation the discussion of biodiversity.

The second element develops studies in specific locations or countries, providing the basis for detailed analyses of the large-area analyses provided by the first programme activity. These site-specific studies serve multiple functions. At one level, they provide an ideal basis for developing field validation and accuracy assessments for the large-area analyses. At another level, they provide the basis for detailed temporal analysis of the dynamics of land-cover change, emphasising the analysis of land-cover transition sequences and the issue of land use and the dynamics of secondary growth turnover.

Focus Activity 2.4. Analysing the spatial relations of land-cover change

New tools of geographic information systems and computer analysis have made it possible to develop quantitative analyses of spatial relationships associated with land-cover change. An important need is analysis of the geometry of land-cover conversion and its associated effect on forest fragmentation. Current approaches to analysis of effects on species composition relate the area of cover converted to species-area curves obtained from empirical data. There is, indeed, a paucity of data on rates of land-cover change, and it is the intention that Activity 2.2 will address this critical analytical requirement. It is becoming clear, however, that the effect on habitat fragmentation is also related to the geometry of the disturbance (as well as the type of cover which replaces the changed cover), indicating that the spatial pattern of land-cover change and the fragmentation of the landscape is the crucial measurement to be made.

The fragmentation of a landscape is a land-use question; the use to which a landscape is subjected results in different patterns and geometries of land cover. For instance, small patches of cleared land are created by small farmers in tropical forests, while large rectilinear patches are created by largeholder cattle ranchers. Different land use influences pattern and geometry, and different patterns and geometries have different effects on the environment. Detailed examination of sites across an organised suite of situations is an important activity to be linked with Focus 1. Effort must be made to compile detailed assessments of this kind if the community is to begin to understand the effects of land-cover change on ecosystem structure and function, and couple this understanding with analyses of the indirect effects of climate change.

Spatial analysis of land-cover changes, as associated with various physical, social, demographic, and economic factors (e.g., distance to roads, soil type, population density, population structure) could elucidate fundamental issues in the land-cover research. For instance, there is a view that population growth is directly related to land-cover change, yet there have been very few direct empirical analyses across a range of scales which explicitly test this hypothesis.

Focus Activity 2.5. Observing the proximate causes of land-cover change

The human proximate causes of land-cover change are the immediate land-management strategies employed that convert cover from one type to another or modify an existing cover type. If it were possible to measure quantitatively the proximate causes - their magnitude, frequency, and geographic distribution - better understanding of the (non-linear) links between human activities and land-cover change consequences could be developed. A large number of proximate causes exist, and identifying the most critical for monitoring and study requires a systematic assessment as proposed in Activity 2.4. Since biomass burning is one of these, we use it to illustrate.

On a global scale, biomass burning is one of the more important proximate causes of land-cover change. It is a sources of carbon dioxide in humid tropical forests (e.g., Skole et al. 1994). In savanna systems it is also an important source of trace gases and particulates (Crutzen and Andreae 1990). It should be noted, though, that the annual regrowth of savanna systems makes savanna burning less important as a source of carbon dioxide. In the boreal zone, the stochasticity of fires is an important consideration. Biomass burning and non-point source emissions are poorly documented at a national scale, and accurate information is needed for national emission inventories.

The process of burning is an important step in the conversion of natural systems to agriculture, removing unwanted herbaceous cover and releasing nutrients to improve soil fertility. In the tropics, there are two distinct types of anthropogenic biomass burning. The first occurs when natural ecosystems are initially cleared. This burning is often associated with deforestation, but also occurs in savanna and grassland systems opened for the first time. The second is the repeated burning of existing savannas or pastures on a short rotation as a form of land management to maintain forage productivity.

Biomass burning in temperate and boreal ecosystems has not been extensively studied, but could be important. There are two general issues. The first is gaining a better quantitative understanding of the anthropogenic fires, or fire suppression, as a form of land-cover change in mature ecosystems. The second is determining how the temporal frequency of natural fires may change over time, and in turn influence the global budget calculations during the time period of observations (i.e., the period for which atmospheric records exist). There are very few data on the timing and distribution of fires worldwide (v. Pyne 1991). This impedes progress in global change research as well as international policy. There is, as yet, no operational mechanism for the monitoring of fires, which requires daily global observations.

No study has yet attempted to define the relatively fine scale (less than 20 km) spatial and temporal (daily) distribution of biomass burning over time. There are a number of advantages to developing a geographically referenced analysis of terrestrial carbon fluxes in the tropics. For instance, the wide range in estimated current net flux of carbon results, in part, from uncertainties concerning the kind of vegetation converted to human uses and the rate of tropical deforestation. Since current analyses have not been able to geographically co-register maps of land cover with maps of land-cover conversion activities, such uncertainty might be resolved, or precisely defined, by making geographically detailed analyses (Emanuel, Shugart and Stevenson 1985; Houghton et al. 1985; Emanuel et al. 1984). Among other things, this would permit the linking of flux estimates to tropospheric chemistry models, atmospheric circulation models, and direct observations.

Focus Activity 2.6. Developing empirical diagnostic models

Direct measurements alone will not provide enough understanding to analyse the driving forces of land-cover change. Thus, linking observations at a range of spatial and temporal scales to empirical models provides a comprehensive approach to understanding land-cover change and at the same time provides important inputs to policy. Assessment of the magnitude and ecological implications of land-cover change is most relevant and useful when it is accompanied by modelling the linkages between socio-economic configurations and the processes of changes.

The primary utility of models is to provide a systematic approach to understanding a research problem. An important aspect of the work described here is the link between direct observations, case studies, and models in an effort to test or identify dominant features of land-cover change. Development of diagnostic models can lead to an improved understanding of the current and recent situation and at the same time provide credible, geographically-referenced predictions. The length of time over which a prediction is valid is a function of the persistence of the observed phenomena. There is evidence to suggest that much, if not most, land-cover change is spatially and temporally persistent over 10 to 15 year intervals. It should be noted, however, that certain events can alter trends significantly and rapidly. Changes in political, institutional, and economic conditions can cause rapid changes in the rate or direction of land-cover change. Therefore, an effort to understand the primary kinds of influ-ences which cause land-cover change trends to diverge rapidly is also an important component of this programme.

It is possible to develop models with considerable spatial resolution in the scale domain of 1:250,000 with horizontal resolution of less than 1 km. For an in-depth perspective see Lambin (1994). Markov chain models provide one approach to empirical models of the land-cover conversion process. The central mechanism of a Markov chain is a probability function which refers to the likelihood of transition from one cover to another cover. The probability function can be static over time (assumes stationarity) or can be adjusted an specific intervals to account for changes in the stationarity of the processes controlling the transition sequences. The probability function and transition sequences can be derived from direct observations using satellite data. Another appropriate model framework is the suite of logistic function models. These models have been used in various case studies to account for changes in the rate of land-cover conversion under constraints. It is conceivable that these two models can be combined and adapted for the spatial diffusion process.

Another class of empirical models includes the regression models, which utilise a system of observations in conjunction with ancillary variables, such as socio-economic data, to identify explicitly the causes of land-use change. These types of models attempt to relate rates of cover-conversion to data expressing the various hypothesised driving forces or proximate causes of deforestation, although they could be applied to modification as well. Regression analyses can be conducted in two ways: by cross-sectional analysis (i.e., at one point in time across a large number of specific locations), or by panel analysis (by relating change in cover during an interval of time to changes in other variables during the same interval across a large number of specific locations). Because of requirements for relating data at specific locations and times, there is a strong requirement for direct observations with detailed spatial resolution.

Spatial statistical models constitute a third class of empirical models. These models have been developed in recent years as a response to the availability of remote sensing, geographic information systems, and multivariate-multitemporal mathematical models. This approach consists of analysing land-cover conversion in relation to geographically referenced data on natural and cultural landscape variables.

In essence, these classes of models form a constellation of approaches which, when taken together, can be used to analyse when (Markov and logistic), why (regression) and where (spatial statistical) land-cover conversion (or modification) processes operate. The suite of empirical models can serve as a foundation upon which mechanistic and systems dynamics models can be built, the essential feature being the use of direct observations of spatial phenomena.

The development of spatially explicit data and empirical models of land-cover change will benefit spatially aggregated macroeconomic models by providing a means for spatial disaggregation of results at finer spatial scales relevant for watershed and basin scale biogeophysical models. For instance, macroeconomic analyses produce estimates of agricultural land over time as a function of various national and international factors. It is also important to know, however, how much new arable land will be derived from various ecosystem types and where in a watershed, basin, or ecotone the conversion will take place. Moreover, it is also important to know if new land will come into production through the conversion of native forest, fallow forest, or through degradation (but not outright conversion) of forest.

Empirical diagnostic models differ somewhat from the mechanistic prognostic models described below. Although somewhat restricted in their ability to explain the underlying processes which control the conversion process, they are well grounded in observational data and their representation of actual conditions, including conditions relating to the measurements made, such as spatial and temporal dynamics. Thus, while the models described in the next section (Regional and Global Models - Framework for Integrative Assessments) provide a basis for prognostic analysis of future trends for purposes of determining policy responses to current trends and conditions, the modelling approach framed here provides a basis for detailed description and analysis of current situations. The two approaches are obviously complementary.

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7. Focus 3: Regional and Global Models - Framework for Integrative Assessments

Introduction

Developing the basis for a new generation of LUCC models is a major task requiring substantial work in both database preparation and methodological innovation (Fig. 14). There are, however, near-term needs for more precise land-use/cover change projections arising from the Intergovernmental Panel on Climate Change (IPCC), the Framework Convention on Climate Change (UNFCCC), and other international bodies. Focus 3, therefore, should follow a two-track approach: a short-term or "fast " track and a longer-term "development " track. The fast-track approach (Focus Activity 3.1) should review and extend existing regional- to global-scale agricultural, grassland, and forestry models to give more reliable land-use/cover change projections over the short term (2-3 years); the development approach (Focus Activities 3.2-3.7) should seek to create a new model structure over a longer term that is capable of a fuller representation of land-use/cover change and its main driving forces. Both of these approaches need to (i) elaborate a methodologically rigorous yet flexible structure for the models capable of including the understanding of driving forces and their LUCC impacts derived from the socio-economic situation analysis of Focus 1 and the spatial analyses of Focus 2, and (ii) extend the structure of current models to obtain a geographically more detailed and sectorally more complete representation of the full range of land uses, of national economies, and of rural-urban linkages.

Focus 3 should develop an integrated model system capable of representing and projecting the major driving forces highlighted in this report and elsewhere by the IGBP/HDP (Turner 1994; Turner, Moss and Skole 1993). Different opinions exist on the robustness of long-term projections of various driving forces; models, then, must be constructed so as to be sensitive to the range in those projections. Development of databases and modelling techniques for the more complete and interrelated representation of crop, livestock, forest, and non-agricultural activities must be undertaken. The science/research plan seeks to develop approaches that advance the state of that modelling "horizontally " between sectors and "vertically " through economic and physical levels:

Aims

(i) Develop both an integrating framework and a range of dynamic and geo-graphically explicit regional and global models capable of simulating the major socio-economic and biophysical driving forces of land-use and land-cover change, including major feedbacks from land-use and land-cover change to those forces and to global change. The models should be able to handle interactions at several spatial and temporal scales.

(ii) Provide robust projections of land-use/cover change and associated biophysical parameters, including vegetation attributes and resource accumulation and degradation, for periods of 50-100 years and a spatial resolution of approximately 10 by 10 km to 50 by 50 km. The appropriate scale will be a matter of early consideration in the project/programme.

(iii) Improve understanding of (a) the local, regional, and global dynamics and consequences of the relationships among the main driving forces and land-use and land-cover change; and (b) the sensitivity of land-use and land-cover change to exogenous variables (e.g., technological change, demographic and economic development, consumer preferences, land-use related policies, and environ-mental conditions).

Activities

The activities of Focus 3 are designed to interact with those of Focus 1 and Focus 2, and take advantage in the short run of the experience and investment accumulated to date in global-scale analyses of agriculture and the forestry sector. Ultimately, Focus 3 should create a new framework for integrating regional and global models representing biophysical and human drivers to project land use and cover in a geographically explicit way.

Focus Activity 3.1. Extending existing regional and global models projecting land use and land cover

A number of the existing global agricultural and vegetation models deal in some detail with crop-related land-use/cover change, but they take insufficient account of forest and rangeland/pastures, and they do not formally, or only weakly, link the economic production modules to biophysical processes. They also tend to emphasise the spread or expansion of land uses and covers (v. FAO 1993a). Studies show, however, that at the global and regional levels (save in the tropical frontiers) land-cover change from expansion has been slowing in recent decades, reaching a current rate of perhaps less than half of a percentage point per year (FAO 1993a). An important issue for the future is likely to be the biophysical and biogeochemical consequences of land-use changes in place, particularly their intensification. Existing agricultural models could provide meaningful projections of this intensification in the short term. Furthermore, there are forest, livestock, and biophysical process models available that could complement current agricultural models, either by their partial integration or by iterative application. This accomplishment would add to the robustness and breadth of interim projections from existing models and extend their role in model development.

Existing models can be improved in several ways: by (i) increasing their robustness to project land-use/cover change for periods of 50-100 years and, where possible, at spatial scales from the sub-national (regional) to the global; (ii) qualitatively and quantitatively improving understanding of the links between land use and cover change; and (iii) testing ways of representing and relating crop production and resource accumulation/degradation processes. These improvements should be viewed as immediate goals.

Global-scale models of agriculture and forestry can be improved for LUCC in two basic ways with modest investments. They can be strengthened by integrating (e.g., formal or informal protocols) the analyses of agriculture, livestock, and forest components. This improvement could be achieved by drawing on several models, such as the IIASA World Agriculture Model (Fischer et al. 1988), FORENA (Solomon 1986), the IIASA Global Forest Trade Model (Kallio et al. 1987), CENTURY (Parton et al. 1987; Parton et al. 1988), EPIC (Williams et al. 1984), FLIPSIM (Richardson and Nixon 1986), IMAGE 2.0 (Alcamo 1994), and others appropriate for data or relationships between driving forces and land-use/cover change. In addition, they can be extended in their representation of production processes to include important physical and biochemical aspects, such as soil erosion and soil nutrient balance calculations. This work could also link to Focus Activity 3.4 (below) for the development of improved ways of interfacing with the full range of economic and biophysical process models.

Some progress has been made in developing and linking regional land-use models (sometimes called Land Use Allocation Models, or LUAMs). They have examined the sensitivity of regional land use and changes to (globally-driven) commodity prices and (globally-agreed) trade practices (e.g., Parry et al. 1996). A range of such models should be used to explore the possibility of developing a hierarchy of models that more effectively captures the regional effects of global driving forces.

Considerable progress has been made in reconstructing the history of land-use/cover change over the past 100 to 150 years (Richards 1990; Williams 1989). This work has made it possible to estimate the roles of past factors influencing the pace and rate of different changes, but more work is needed to characterise these roles in detail and to provide an empirical basis for model construction. It should focus on the period 1960 to present (but 1900 to present would be useful as well).

It is important to define more precisely the relationship between land-use change and the vegetation/cover attributes that play a major role in surface energy budgets, through their impact on surface resistance and albedo, and in greenhouse gas fluxes. Is the replacement of long fallows (forest or bush) by perennial plantation crops, or paddy rice by wheat important? Similar questions arise with regard to changes in land management practices, such as the shift from ploughing to minimal tillage without any change in the cropping pattern. Such conclusions may have an important bearing on the level of detail or projection precision to be aimed for in the development of the new models. The task is to use empirical analysis or semi-analytical models to determine the significance of the relationships between land-use/cover change and vegetation attributes, and if they are found to be important given the overall objectives of the science/research plan, to parameterise them for use in Activity 3.2 and following.

Land-use/cover change data compiled from international sources, national institutions, or case studies must be compatible. At the moment, however, there are several land-cover and land-use classifications in operation, leading to serious inconsistencies between datasets (v. Young 1994; MŸcher et al. 1993). Several UN agencies and international institutions, in particular UNEP and FAO, have been working on this problem and seem close to agreement as to the classification systems to be adopted (UNEP/GEMS 1994). Focus 3 should not attempt to construct its own classification but should use these forthcoming classifications for the fast-track approach (understanding that the development-track approach must couple with Integrating Activity 1 on data and classification, described in Section 8). Considering the above, provisional long-term projections of land-use/cover change could be developed. They should focus on changes over the next 50-100 years, estimate possible biophysical and biogeochemical impacts arising from land-use/cover change, and improve understanding of the dynamics of land-use/cover change as a result of the main driving forces. This effort should also apply sensitivity analysis and determine priority areas for: (i) the activities undertaking the development of a new model structure, and (ii) the relation to other LUCC Foci. Finally, Focus Activity 3.1 should produce results within a 3-5 year time frame of implementation.

Focus Activity 3.2. Creating a new structure for modelling land-use and land-cover change

The longer-term aim of Focus 3 is to create a new structure for LUCC models possessing flexibility and a sound theoretical basis and the ability to integrate a variety of approaches. There is evidence that, worldwide and in most regions, land-use/cover change is taking place increasingly under the influence of the market and will continue to do so over the longer term. It is justifiable, therefore, to start from a model based on economic theory. It is equally clear, however, that many forces distort or attenuate the price signals to which land and water resource users respond and that some of these users are socially or physically isolated from such market signals. These conditions must find their way into the model structure.

Either the normative or the descriptive approach can be used to model human behaviour. The normative approach solves a welfare programme that maximises a weighted sum of agents' welfare subject to technological constraints. The welfare programme is decentralised to the greatest extent possible under the given model specification. Under decentralisation, all agents individually solve an inter-temporal maximisation problem (e.g., utility maximisation for consumers, profit maximisation for firms, subject to political intervention, as well as technological, social, cultural, and environmental constraints). If markets are competitive, then agents take prices as given, and prices are the only variables that affect them. There may be many other variables that individual agents have to take as given, however, such as taxes or the level of provision of collective consumption. Prices can be obtained on competitive markets, if these exist. Other controls in the welfare programme have to be set optimally by a government or some other higher level authority, taking the preferences of the individuals into account. The normative approach is helpful at the conceptual level in showing socially desirable and economically efficient courses of action. It disregards the lack of information that individuals and even governments face in practice, however, and it also neglects the fact that governments and other organisations often pursue other interests than the maximisation of social welfare.

The descriptive approach to economic modelling takes an empirical view of the behaviour of individuals and governments and specifies functional relationships that are estimated statistically and assume limited foresight. It permits the development of models that can more easily be validated on past observations and used for short- to medium-term policy simulations. Scenarios can be formulated that show how specified changes of critical parameters will affect outcomes. Applied models of several types are available that could be extended to include natural resources in a more explicit way. The number of possible variations in the behavioural part may be prohibitive, however, and scenarios will not be optimal in any sense, nor can the distance of a simulated solution from an optimal solution be assessed. Hence, as the time horizon of the issues under investigation is long, it would seem unwise to rely only on such descriptive models.

Moreover, given that most increased crop and livestock production is projected to come from use intensification, models should be sensitive to technological change. Most existing land-use/cover change models treat this change with simple exogenous assumptions. The new structure should seek to embody endogenous technological growth and price formation, and use suitable approaches to include risk, uncertainty, and any major non-market or institutional features of the driving forces that may be identified through Focus 1. Finally, given the great spatial heterogeneity in both the quality and quantity of land resources and in the driving forces, the new structure should make the land-use/cover change projections geographically explicit.

Both the driving forces of land-use/cover change and their consequences in terms of altered use and cover have varying expressions at different scales. It is therefore necessary to develop models that capture adequately the different interactions at (and between) regional, national, and global levels. Regional and national models need to be based on detailed georeferenced bases of information relating to land-use potential. These models should be receptive to variable input costs (e.g., fuel, fertiliser, feeds), variable demand (reflecting demography, affluence level, and so forth), variable production conditions (e.g., technology, climate), and variable prices (reflecting global demand-supply functions). An interactive linked system of both regional and national models would then comprise a set of global land-use and land-cover models.

This facet of Focus 3, therefore, seeks to build on the strengths of existing models and recent theoretical or conceptual advances to give (i) a more fully integrated representation of the driving forces for land-use/cover change, and (ii) a more complete and more dynamic and geographically explicit representation of these driving forces, their interactions, and their impacts. This effort raises some major issues.

The LUCC research theme spans a multitude of different systems and processes, each with its characteristic scale and dimensions, data availability, and nature. Current databases can be divided into two major classes: biophysical and socio-economic. The biophysical and environmental attributes of land cover, such as soil, topography, vegetation, and climate, are generally characterised by continuous changes over the surface of the earth and have been expressed in a geographically explicit way using GIS technologies. There are a number of GIS datasets on which to draw, and so the task may be more of catalysing gap-filling activities than of taking the lead.

The biophysical datasets are georeferenced and globally available on a grid or polygon basis. The most relevant databases for this project/programme include: FAO/UNESCO Soil Map of the World (FAO/UNESCO 1974; FAO/UNESCO 1988; FAO 1993c), climatic data (Leemans and Cramer 1991; Chadwyck-Healey 1992), GLASOD: World Map of the Status of Human-Induced Soil Degradation (ISRIC/UNEP 1991), United Nations list of national parks and protected areas (IUCN 1990; WCMC 1992), and various other compilations of relevant data such as topography and vegetation (Kineman and Ohrenschall 1992). Several international organisations (UNEP-GRID; UNEP-GEMS; FAO; ISRIC) and research programmes such as IGBP, WCRP, and HDP are currently also developing and compiling global datasets. As with land-use classification, the objective should be to draw on and not duplicate other activities. The most promising new databases for regional- to global-scale studies could be SOTER (van Engelen and Ting-tiang 1993), land cover by the IGBP-DIS (Townshend, 1992), and, possibly in the near future, the Global Terrestrial Observing System (GTOS; Heal et al., 1993).

The situation is quite different for socio-economic datasets, in part because of HDP-DIS remains in its developmental stage. Those relevant and required for analysing LUCC processes as proposed here, from national to village and household level data. There is a wealth of socio-economic databases available at the national level. A number of them, mainly economic data, are summarised in Yohe and Segerson (1992). The most appropriate datasets for this project/programme are from (i) the UN: Demographic Yearbook, National Accounts Statistics, Statistical Yearbook, World Economic Survey, Energy Statistics Yearbook; (ii) the FAO: Production Yearbook, Trade Yearbook, Yearbook of Forest Products, Yearbook of Fishery Statistics, Fertiliser Yearbook, AGROSTAT-PC (FAO 1993b); (iii) the ILO: Yearbook of Labour Statistics, (iv) UNEP: UNEP Environment Data Report, (v) the World Bank: World Tables, World Development Report; (vi) the IMF: International Financial Statistics, Balance of Payments Statistics Yearbook, Government Finance Statistics Yearbook, Direction of Trade Statistics Yearbook; (vii) OECD: Annual National Accounts, OECD Economic Surveys, OECD Financial Statistics; and (viii) World Resources Institute: World Resources reports. Compilations of these datasets are produced regularly in annual or biennial cycles.

In addition, there are relevant national level data provided by FAO in five- or ten-year intervals. The FAO Forest Resources Assessment (FAO 1993d; UN-ECE/FAO 1992) surveys forest cover every ten years. The World Census of Agriculture (FAO 1985-89; FAO 1986; FAO 1992), carried out every ten years, is the major source of international statistics on agricultural land use. Information on food supply and consumption is published in FAO Food balance sheets (FAO 1991). Comprehensive datasets providing national (for 141 countries) and broad regional time-series data regarding economic, agricultural growth, performance, production and trade indicators are published by USDA (USDA 1993). Finally, CIESIN (US) has begun to develop various data sets available in digital form, particularly that on population.

The listing above illustrates that many global and regional databases have been developed and can be suitable for the LUCC activities. The data should be evaluated on criteria such as quality, comprehensiveness, scale and resolution, time-span and coverage, relevance, and compatibility with internationally accepted standards. With respect to the last, methods should be developed to translate national standards (e.g., soil classifications) into those internationally used.

National-level data are not sufficient for the needs of Focus 3, however. They are seldom available in a GIS form, but are usually supplied aggregated in a tabular format by economic or political entities, such as districts. National and, less often, provincial boundaries have been digitised (although both change). For many of the other datasets relevant to the socio-economic driving forces, the situation is much less favourable. Either the data are not available at the sub-national level, or they are so out of date as to be of little value. The task here may therefore be more proactive, including the development of proxy measures and the preparation of guidelines on data characte-ristics and formats. Comprehensive modelling of land-use decisions requires a description of economic activities at the sub-national scale, including relationships between economic sectors, and, in particular, data on production conditions, require-ments, and multiple functions of major land-using activities, such as agriculture and forestry. The geographic units of the integrated model system will need to be described in terms of social attributes, economic data, land properties (e.g., topography, climate, soils, water, ecology), resource use information, land management, infrastructure and political organisation (e.g., FAO 1994c). Such georeferenced databases with global coverage do not exist, although relevant portions have been compiled in several national-level studies (e.g., Himiyama 1992; FAO/IIASA 1993).

One of the methodological innovations required in this project/programme is to bridge the different characteristics of data. An obvious link is to create a geographically explicit database for the location and extent of the selected economic or political units. For land-use studies, however, it is often inappropriate, especially for larger units like provinces or countries, to assume that the environmental or socio-economic properties of these units are distributed homogeneously. Most often, the environ-mental properties are obtained at a much higher spatial resolution. Many current global databases have a resolution of 10 to 50 km, whereas satellite images can have resolutions as low as 10 m. The heterogeneity of biophysical and environmental data within an economic unit can be used to study historic and current land-use patterns and to develop models to analyse future patterns.

The complex and multi-dimensional driving forces must be carefully structured and parameterised for implementation in regional or global models of land-use and land-cover change. Type, spatial characteristics, and temporal scale of a driver must be distinguished. For instance, it may be possible to describe the driver's influence in terms of objectives of land owners, of constraints to human activity and land use, or as dynamic accumulation and degradation processes that affect physical land-use conditions and constraints or change the policy focus and value system.

A hierarchical decision structure is needed that links producers reflecting a range of production conditions (e.g., introduced as prototypical farms, ranches, and forest enterprises) to consumers, differentiated by income class, location (i.e., rural or urban), and position in the processing, marketing, and final demand chain, and to govern-ments acting unilaterally or multilaterally. A decentralised representation of a large number of agents in the model system may be most appropriate to support the overall objectives of Focus 3. It allows for imposing structure at the higher levels of social and political organisation by implementing market clearing conditions, national or regional constraints on commodity and resource flows, and budget constraints; but it also allows for a fair amount of flexibility to include geographic, socio-economic, and cultural specificities of different regions.

For each group of actors, modelling the key behavioural responses in terms of their geo-political/cultural objectives and constraints is required. This calls for innovative thinking in conjunction with Focus 1 and Focus 2 on the application of decision theory, welfare economics, and spatial statistical analysis.

Technology is used here to embrace all innovative processes that enable land, in whatever application, to meet the demands placed on it at socially acceptable costs. Such innovation may involve movement along existing production levels exploiting opportunities for factor substitution (e.g., capital for land and labour), or movement from one production surface to another, with implications for resource use efficiency and profitability, land-cover attributes and material balances. In many models, technological change has been treated as exogenous to the economic system. But much work has focused on the evolution of technologies as pressures on land mount (e.g., Boserup 1981). This work suggests that technological shifts are, more often than not, endogenous to the particular system. Mechanisms for endogenising technological change will be inserted into models used for long-range projections. They will draw on established theoretical concepts and empirical findings on induced innovation and intensification and the effect of population pressure and market development on technological change (e.g., Hayami and Ruttan 1985; Pingali, Bigot and Binswanger 1987; Kates, Hyden and Turner 1993; Tiffen and Mortimore 1993).

The actors in the social and economic systems (e.g., producers, consumers, and governments) act with more or less foresight, depending on the severity of individual short-term constraints, amount of information available to them, and prevailing norms and value systems. In a realistic assessment, dealing with uncertainty is unavoidable. Uncertainty is relevant in relation to land resources, not only because of the variability of weather conditions, but also because of uncertainty about processes of environmental degradation, future costs and benefits of investments, production functions, and availability of resources.

Focus Activity 3.3. Extending the horizontal linkages

Ultimately, the aim of LUCC models is to employ a more fine-tuned matrix or fabric of land uses and cover to project change. To do so requires LUCC models to account more fully for the spatial variability and dynamics of land-use sectors, including enterprises and interactions within each sector. Predominantly market-driven and non-market-driven enterprises of a sector, multiple sectors, or both, for example, commonly co-exist within a region. Many parts of the developing world contain market-driven logging along with subsistence cultivation, the two interacting through particular local dynamics that lead to land-use and land-cover outcomes that would differ considerably if one or the other sector were not present or were driven by different forces (e.g., Kummer 1991; Kummer and Turner 1994). In addition, the differentiations and interactions between urban and rural sectors must be elaborated. Urbanisation is a global phenomenon (e.g., Simpson 1993), and urban demands increasingly influence rural land use. This influence is a given in developed economies, and urban-hinterland use models have a long tradition (e.g., Chisholm 1962), even identifying global cores and hinterlands (e.g., Wallerstein 1974). Similar dynamics are now influencing the peripheries of less developed economies (e.g., Mortimore 1993), and they could be incorporated into land-use/cover models.

Economic models usually organise production activities in terms of economic sectors. At the highest aggregation level, the following sectors are often distinguished: agriculture, forestry, energy, and other non-agriculture. Sectors with a strong relation to land use must be further subdivided; in particular, agriculture and forestry. In each sector a variety of production conditions will need to be distinguished. For example, agricultural production in a geographical unit can be described as cumulative output from a collection of representative farms. Such differentiation should reflect major differences in production conditions (agro-ecology, farm resources, infrastructure, and so forth) and, for the purpose of the land-use and land-cover change theme, relate to the dominance of various driving forces (i.e., prototypical situations or constellations of driving forces). To be empirically founded, this requires appropriate georeferenced datasets and advanced methods of spatial statistical analysis, and needs to build on information derived from Focus 1 and Focus 2 activities.

Models must devise suitable mechanisms for distinguishing between urban and rural demands, possibly by differentiating spatially and economically between urban and rural sectors. The increasing urbanisation of the world population has triggered major qualitative and quantitative changes in pressures on land use and land cover that must be modelled through a more complete representation of the non-agricultural economy. The mechanisms should be related to urbanisation and rural-urban income differentials, in part to capture land-cover change for human settlements and infrastructure, but more importantly because of the push-pull factors underlying rural-urban migration. These are likely to reduce pressures for marginal land development and increase pressures for the intensification of production and the consolidation of small land holdings stemming from labour shortages or higher wage rates.

Focus Activity 3.4. Refining the vertical linkages

Land uses are influenced by the nature of consumption-production relationships and by the biophysical impacts and feedbacks following from the use (Leemans 1992; Solomon et al. 1993). These vertical linkages must be more fully incorporated into LUCC models. It is apparent that the links between consumption and production are more critical to land-use/cover change than previously recognised in global or even national models. In the long term, income growth, rapid urbanisation, education, and exposure to other cultures will all have major impacts on demand patterns and hence on land-use/cover change, biogeochemical cycles, and other aspects of global change. For example, there may be a significant global shift from rice to wheat (Crosson and Anderson 1992), with important implications for pressures on wetlands, greenhouse gas emissions, and nitrogen cycles. The demand patterns of high income groups in a country are currently a reasonable indicator of what the rest of the population will do when their incomes rise (FAO 1993a; Parikh 1994), but the long-term validity of this claim needs to be tested. Most existing land-use/cover change-oriented models make only limited allowance for urbanisation effects on demand patterns for both food and fuel; yet they can be substantial, leading to important impacts on land use and cover. Thus the structure and dynamics of demand patterns and their implications for land-use change need further analysis.

Likewise, the biophysical impacts of land uses and their ultimate feedbacks on the uses need careful consideration, not only because they are inadequately considered in most socio-economic models, but because their nature and significance are contested. Soil and soil nutrient losses, degradation of grasslands, and depletion of aquifers affect the land uses that gave rise to them. The time scales of such losses must be addressed as well because of their implications for sustained land use, about which many assess-ments may be overly pessimistic (e.g., Bie 1990; Nelson 1988; UNEP 1992). Attention must also be paid to improvements in the biophysical condition of the land by and for particular uses.

At least three aspects of the models need attention. First, further analysis is required of the factors underlying shifts in cereal demand - for example, from rice, maize, or root crops to wheat (Ingco 1990; Mitchell 1991). Such shifts may have few implications for land-cover change per se, or for some aspects of land use in that the vegetation attri-butes of many cereals are broadly the same, but they may be important for biogeo-chemical cycles. Second, food-demand analysis needs to be expanded over longer time periods. Most detailed analyses have covered periods of only 10-15 years; nonetheless they show strong national differences, even between culturally similar countries (e.g., Japan and Korea), and complex real price and income effects that need to be separated. Third, major headway needs to be made on data collection and empirical analysis of the effect of urbanisation on the demand for livestock products, and in turn on the structure of livestock production and imports. It has major implications for land-cover change (i.e., conversion or reversion of range or more intensive manage-ment of grazing land via the demand for feed grains of domestic or international origin), but has not been adequately analysed. This work should be closely allied to the linking of the key actors/agents of land-use/cover change (Focus Activity 3.2); to the development of enterprise models, which will include different forms of livestock production (Focus Activity 3.3); and to the research on rural-urban linkages (Focus Activity 3.3), because it is strongly related to questions of rural-urban income differentials and altered lifestyles.

To project land-use changes into the second half of the next century, it will be necessary to describe resource accumulation processes and feedbacks and non-linearities of impacts on land productivity. Here, the terms "resource" and "accumulation" are used in a general sense. They include human resources (e.g., population number, distribution, age structure, migration flows, fertility, skill level), renewable and non-renewable natural resources (e.g., soils, minerals, water, air), biological resources (e.g., biodiversity), and economic resources (e.g., capital stocks and machinery). Accumulation also includes various degradation processes, physical (e.g., soil erosion, degradation of soil structure, groundwater depletion) and chemical (e.g., acidification, salinisation, and toxification of soils, depletion of the ozone layer, nitrification of groundwater).

There are two main possible approaches. One is to use separate economic and biophysical models and link them so that the output of the former becomes an input for the latter or vice versa. This approach has the advantage of relative functional simplicity and transparency, perhaps at the expense of theoretical rigour. The alterna-tive is to find some practical way of introducing selected biological processes directly into the economic model. Both approaches need to be explored. Given the large uncertainties in the dynamics of many biological processes, however, it may be best to concentrate on the former or try for a hybrid approach that only uses the more complex approach where its theoretical and empirical foundations are well established. A complicating factor is the different time and space scales at which these processes operate.

Focus Activity 3.5. Introducing water into the land-use/cover change projections

In many areas of the world, water usage has approached or will soon approach the limits of water availability (Falkenmark 1989; Gleick 1993; Kulshreshtha 1993). Agriculture has been and continues to be the principal consumer of water worldwide and the source of major aquifer depletion (e.g., Postel 1993). Many analysts expect that the intensification of agriculture in the future will centre on the expanded and intensified use of irrigation (e.g., FAO 1993a). It is of critical importance, therefore, to improve our understanding of how, in the long term, competition for water, its distribution mechanisms and price, and water-related policies may affect land-use and land-cover change, and conversely, how land-use/cover change may influence the water cycle and water supply. This effort requires the introduction of the price, policy, and institutions of irrigation water into the crop production function. It also requires the modelling of various environmental aspects of water use, such as soil salinisation and toxification and consequently crop productivity decline.

To provide information on future availability of water resources, a hydrologic modelling system needs to be developed. Several hydrological models of varying complexity and sophistication have been used to investigate the effects of predicted climatic change on water resources (e.g., Bultot et al. 1988; Kite 1993; Strzepek et al. 1994; WMO 1987). The importance of feedback mechanisms that operate between a continental surface and the overlying atmosphere have been demonstrated for West Africa (Savenije and Hall, 1994). Modelling the impact of land-use/cover change on water supply requires improved datasets and understanding of complex biospheric mechanisms to capture indirect effects as well, such as the impact of change in upper basin watersheds on lower basin vulnerability.

The amount and intra-annual variation of water supply depend not only on the abundance and reliability of water resources but also on the development and management of a water resource infrastructure consisting of dams/reservoirs, pumps, canals, pipelines, and wastewater treatment facilities. These factors could be modelled through a water development sector that is price- as well as policy- and institution-driven. Where possible, modelling should refer to georeferenced water stocks per-mitting the representation of major river basins (Winpenny 1994). In addition, it is clear that water infrastructure is an important aspect of national development in terms not only of water supply but also of flood protection and its relation to land use and cover.

Land use, population, and lifestyles are the driving forces behind water demand. Agriculture is the primary water user globally. Changes in land use could have dramatic impacts on water demand. Demand for water is also much influenced by economic and technological factors. Water use is not fixed per unit of land but depends on the crop being grown and the agricultural/irrigation technology and management used. In many cases, therefore, it may be more economical to adjust water demand through increasing efficiency of water use rather than increasing water supply. Yet changes in agricultural technology require capital, creating competition with other sectors of the economy for scarce investment funds. Of equal importance to water supply and demand are legal and institutional factors (FAO 1994a) and political arrangements, such as international agreements in the case of large international rivers. Successful modelling of water demand and distribution will require the assembly of improved national data on water use by sector, including prices and subsidies (e.g., FAO 1994b).

Water supply is measured not only in terms of water quantity, but also in terms of water quality. In the context of land-use/cover change, water quality is a crucial attribute to model (Novotny and Olem 1994). Depending on use, water demand is based on certain levels of water quality. Different land uses can significantly change downstream water quality: agriculture through chemical application and non-point source pollution, industry through point source pollution, cities through non-point source and municipal wastewater pollution. Hence, a simplified simulation of water quality in receiving streams, lakes, and reservoirs and in groundwater is required in the LUCC modelling effort (e.g., Somlyody et al. 1994).

To model the environmental risks of water use in agriculture, two major components are needed: (i) modelling the process of non-point pollution generation from agricultural production and irrigation (Zannetti 1993); (ii) modelling the quality of streams, lakes/reservoirs, and groundwater aquifers that are recipients of this pollution (Thomann and Mueller 1986).

Modelling the generation of agricultural pollution loads requires data on soil types, slope steepness, land use and management, cropping patterns and yields and amount of fertilisers and pesticides applied, as well as coefficients of chemical runoff. A number of detailed process-oriented models of this class are available. AGNPS, CREAMS (Knisel 1980) and SWRRB, SWAT (Arnold 1994) have been extensively applied at the field level and for national assessments. The use or modification of these models would be recommended.

Modelling the quality of streams, lakes/reservoirs, and groundwater aquifers that are recipients of agricultural pollution requires the inclusion of point and vector data in the spatial framework of the model. In addition, the topology of land use and the network of water bodies must be specifically modelled as water-quality impacts are from upstream to downstream. Decay and dilution processes make the distance from the source of pollution important. Surface water-quality modelling should include as a minimum the oxygen, phosphorus, and nitrogen cycles. Where possible, modelling of non-traditional pollutants, such as organic substances and heavy metals, for river water and sediment is suggested. Groundwater-quality modelling should include as a minimum the nitrogen cycle, and possibly the phosphorus cycle, organic substances, and heavy metals.

In addition, particularly severe environmental consequences have been documented in relation to large-scale irrigation (Postel 1992). By far the largest environmental risks of irrigation relate to waterlogging and salinisation. Irrigated agricultural pro-duction also poses the risk of water and soil toxification. Finally, unsustainable over-pumping of water sources in semi-arid regions has led to major drops in water tables and surface water and to large-scale environmental degradation (e.g., Kotlyakov 1991; Micklin 1989).

Focus Activity 3.6. Model validation and sensitivity analysis

The usefulness of a quantitative model for prognostic purposes depends to a considerable degree on its descriptive accuracy. This is particularly so for an integrated model system in which several components are interdependent, and where even the directions of the responses are often not predictable from qualitative arguments alone. Therefore, the models must be subjected to sensitivity analysis and validation, to test how well the models describe the continent/region as it is. The difficulty of evaluating large model systems has often been pointed out (e.g., Lewandowski 1981; Chow and Corsi 1982). There is a wide variety of methods that are applied (Kleijnen 1992). Except for certain classes of models where statistical tests can be applied (e.g., Challen and Hagger, 1983), however, validation procedures are often not formalised, and include subjective judgement for evaluation.

The task of model and data validation will be facilitated by establishing reliable databases and specifying the model system on a solid theoretical basis. Apart from theoretical consistency and rigour in model specification, and, of course, verification of model implementation, testing the influence of unusual data points, testing for misspecification, and testing for alternative specifications, stability of parameters, and past tracking ability will be of importance. The project/programme should attempt to formalise the validation procedure as much as possible.

The sensitivity of model results to changes in critical model variables and assumptions should also be tested. Small differences in the initial constellation of key parameters could lead to major differences in the long-term development paths because of the complexity of feedbacks and cumulative processes that characterise both the socio-economic and the natural resource components of the system. Different methodo-logies are used to assess the sensitivity of large system models (e.g., Klepper and Hendrix 1994; Leemans 1992; Swartzman and Kaluzny 1987) but new techniques must be developed to deal with the complexity of such global integrated models.

Focus Activity 3.7. Scenario specification and simulation

Given the large uncertainties regarding the long-term evolution of key driving forces, such as population growth/distribution and per capita income growth, it is important to establish a number of well-defined scenarios over a plausible range of pathways for socio-economic development and policies to help delineating the possibilities for long-term land-use/cover change and its biophysical impacts. Also, scenarios related to long-term global environmental changes are required that would indicate the sensitivity of land use and land cover to, for example, greenhouse-gas induced climate change.

Scenarios should cover both historically important driving forces as identified in Focus Activity 3.1 and new potentially emerging factors. The complexity of the issues analysed and the large number of possible assumptions on key driving factors conceivable in a spatially explicit model of land-use and land-cover change call for careful selection and methodological innovations in scenario design.

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8. Integrating Activity 1: Data and Classification

Introduction

Data for a land-use/cover change programme will come from a variety of physical and social science sources. This interdisciplinary programme will require close cooperation between the IGBP and HDP Data and Information Systems Offices. Some of the required datasets can be defined now, and these have been described in the sections below; most, however, cannot, so the issue at hand is the development of the process by which these datasets can be defined and acquired.

The first step will be to cultivate collaborative working relations between HDP-DIS and IGBP-DIS. Many of the datasets being developed now by IGBP-DIS will be important for the LUCC programme. The scientific rationale for these datasets, however, has been defined largely by physical and biological requirements; for these datasets to be fully useful, some integration and augmentation with social science data will be required.

The integration of social-science datasets with physical-science datasets is seen as a crucial step in the development of data for LUCC. For instance, in the sections below, the need is articulated for a land-use dataset. This kind of data could possibly be developed using the AVHRR 1 km dataset being developed by IGBP-DIS, but it will also be necessary to integrate with the remote-sensing data other sources of information on land tenure, land management and other factors which will define land use as opposed to land cover. Moreover, it is likely that sharing of data between IGBP-DIS and HDP-DIS will be necessary. The implementation of some formal mechanism for data exchange and collaboration in the development of datasets is therefore necessary.

In the sections below the data requirements are divided into two broad categories. The first relates to the development of land-use and land-cover classifications for the LUCC programme. It is essential that these classifications lead to a refined stratification scheme, in order for the development of typologies and models (Foci 1 and 2, 3 respectively) to begin. The second relates to the development of datasets themselves - the acquisition and organisation of data from new and existing sources, related to both social and physical science.

Classification

LUCC studies will require a global approach to land-use and land-cover classification. While it is understood that there is no such thing as a universal classification scheme, appropriate classifications will need to consider the different dimensions of land use and cover. A sound classification requires the following characteristics:

- It must be comprehensive
- The criteria must be based on inherent dimensions of land use and cover; in this way the land-use and land-cover classification will complement other classifications (e.g., of soils, vegetation, and farming systems)
- The diagnostic criteria for the classification of land use should be those associated with the land use over the long term (e.g., burning is one of the consistent characteristics of shifting cultivation, even though the action takes place in a few hours or in a few days)
- The basic unit of land cover must be a geographically explicit unit (i.e., a unit of biophysical management). For instance, the field/parcel/plot is not a useful unit whereas any unit of biophysical management can be applied to a range of land use. To the basic unit of land cover corresponds the unit of socio-economic manage-ment, which may be geographically different because it sometimes includes non-land-use activities or non-geographically explicit units such as the household
- The diagnostic criteria, independent of the level in the classification, must be differentiating characteristics at the "field " or land-user level, similar to the use of diagnostic horizons in soil classification
- Unlike the basic unit of analysis, which is scale-dependent, the land-use classification as such must be scale-neutral, meaning that the classes at all levels of the classifications should be applicable at any scale or level of detail
- The land-use classification must be a multi-categorical system, with only a few diagnostic criteria and classes at the highest level; at lower levels, the number of diagnostic criteria increases, as does the number of classes; diagnostic criteria used at one level of the classification should not be used again at a lower level.

The higher levels of a global land-use/cover classification should be accepted world-wide. At lower levels, classes can be included or left out depending on the region and the purpose of a study, but these classes also need quantitative boundaries to make some comparison possible. For the biophysical-manipulation meaning of land use, the key attributes for global change research must relate to land cover, and include at least the following:

- The effects of vegetation structure, phenology, and composition
- The effects on physical, chemical, and optical properties of soil and rocks
- Patterns of distribution of biophysical management (or techno-managerial strategies) in space and time
- A quantification of the effects of changes in cover resulting from land use on future potential uses (feedback effects)
- The dynamics or evolution of land use and related cover, as expressed in two fundamental ways: input intensification (increased inputs of matter and energy in time and space) and disintensification (reduced inputs ending in a return to semi-natural vegetation).

For the intent or purpose meaning of land use, the key attributes that allow linkages between the behaviour (decision making) of the land manager and the biophysical manipulations employed must include at least the following:

- The specific structure of the inventory managed (e.g., regrowth forest, beef or dairy cattle, manioc or cassava)
- The major landesque capital requirements for the management (e.g., irrigation, terraces, modern crop varieties, fertilisers, tillers)
- The kind of economic production in which the management unit is engaged (e.g., private ownership, rent/lease, sharecrop, cooperative tenure)
- The dynamics of output intensification and disintensification as expressed in two fundamental ways: yields (output per harvest) and land productivity (output per unit area and time).

Modern information technology, in particular through storage, analysis, and retrieval in thematic and geographical databases, has weakened the need for a rigid global land-use classification. There remains strong agreement within and outside the global change community, however, on the need for a clear and standardised approach to land-use classification and terminology.

Integrating Activity 1.1. Developing land-use and land-cover classification systems

It is unlikely that one classification system can serve the needs of the LUCC project/ programme, given their interest in both biophysical and human use as well as cover. The plan favours the development of a systematic approach to land-use/cover in which the attributes for the three dimensions (biophysical manipulation, purpose, and environmental setting) of land use are clearly defined and for which standardised data can be collected and reconfigured for multiple uses. This activity, therefore, will: (i) determine a minimum set of descriptors to identify and classify land use and related cover; (ii) define a common terminology on land-use/cover definitions for global change purposes; (iii) develop and implement a flexible, multi-dimensional database format on global land use and related cover that will be able to handle the various dimensions of land use and cover, based on improved statistical techniques; (iv) design the structure of a standard global reference classification of land use and related cover in cooperation with FAO and other programmes undertaking such efforts; and (v) develop a common procedure of land-use mapping in the context of global change.

Data

The classification and analysis of LUCC will require a significant amount of new and reformulated data. These data involve land cover, land use, social and biophysical drivers, and proximate activities or land management with the aim of providing resolution from ~1 km to the subnational, depending on the variable. For the most part, data on land cover and various biophysical variables have been more thoroughly assessed in terms of needs and collection format than have those on land cover and social variables. This reflects, in part, the efforts of IGBP-DIS to address land cover. HDP-DIS is in the process of initiating an assessment of the needs for land-use and social variables.

Integrating Activity 1.2. Land-cover mapping

This activity will promote the continued development of high resolution land-cover mapping by: (i) providing a classification scheme suitable for the three LUCC research foci; (ii) developing regional/global land-cover classification maps at 2 km resolution as well as (iii) regional/global land-cover parameter maps at the same resolution; and (iv) coordinating the above with the IGBP-DIS 1 km Land Cover project.

The current distribution of land cover worldwide is not well known (Leemans, Cramer and van Minnen 1995). Regional stratification of vegetation and land-cover types is required for most global change models. A land-cover dataset at a spatial resolution of ~2 km would enable the assignment of variables such as biomass, combustion efficiencies and the like, and would provide a framework for integrating the bio-physical aspects of land use mentioned above. These kinds of data do not now exist, but programmes such as the IGBP-DIS Land Cover initiative are under way to develop them. It would be prudent for LUCC to coordinate its requirements through these ongoing activities rather than initiating new activities.

Beyond the classification or stratification of land cover, it is important to have a comprehensive assessment of vegetation and land cover as it relates to the seasonal patterns of greenness and vegetation phenology. A characterisation of growing season length would be valuable for further elaboration of the biophysical regime in which land-use and land-cover conversion is taking place, and for developing the feedbacks on land-use processes from the physical setting (see Focus 1).

This kind of information is also important for the development of improved global change models, such as those focused on issues of Net Primary Production (NPP), ecosystem metabolism, and carbon cycling. To facilitate the integration of LUCC processes with these models so as to better develop coupled global models, it is important to have coordinated development of such databases. For instance, it will be important to couple net fluxes of greenhouse gases derived from anthropogenic impacts with gross exchanges of gases between the atmosphere and the biota to close the carbon budget in real time. Studies which pull together the exchanges of carbon from deforestation, fossil fuel burning, oceanic uptake, and biotic metabolic exchanges during the period of the last 20 years when these atmospheric measurements have been taken can be important contributions to our understanding of the carbon cycle, and hence one critical facet of global change.

Further, the development of climate-sensitive, process-based ecosystem models which treat the geographical and seasonal variation in phenology, NPP, and gas exchange can be used in the development of climate response analyses. These analyses would support the IPCC process, as well as vulnerability assessments (e.g., IPCC WG II). Such analyses of climate-forced land-cover change would provide a basis for mitigation and adaptation studies. Finally, the feedback between anthropogenic land-cover change from climate change could be explored.

A premise of this Integrating Activity is that satellite remote sensing is the only viable approach to developing global land-cover information. Synthesis of existing maps cannot provide a globally consistent and up-to-date database for the purposes of this programme (Townshend et al. 1991). An activity driven by remote sensing is obliged to address several technical issues, such as a need for agreement on the land-cover classification schemes for carbon modelling. Such an agreement is currently being sought by the IGBP-DIS Global Land Cover Working Group. The proposed Integrating Activity would pursue close involvement with this international activity.

A useful distinction can be made between land-cover characterisation in natural and anthropogenic systems as a function of the spatial scale of land cover. In general, coarse resolution sensors can be used for mapping natural systems; however, the high spatial variability of agricultural systems requires the use of high resolution data. Automated approaches are preferred for high temporal resolution data, whereas manual, automated and hybrid approaches are used for analysis of high spatial resolution data. It should be noted, though, that the impact of seasonality on the interpretation of high resolution data is sufficiently problematic that a combination of coarse and high resolution data may be needed to address anthropogenic systems.

A similar multiresolution approach may be needed to characterise wetlands, an important ecosystem with respect to methane emission.

As mentioned above, it will be important to build on existing programmes where possible. There are several ongoing activities through which a LUCC programme could coordinate its data requirements for land cover:

- An improved global land-cover map is being generated in the US using the global 1 km AVHRR IGBP dataset which has been compiled through National Aeronautics and Space Administration (NASA) funding in cooperation with the National Oceanic and Atmospheric Administration (NOAA) and the European Space Agency (ESA), extending the research presented by Loveland and colleagues (1991).
- A global sample of land-cover test sites is being developed through the NASA EOS Landsat Pathfinder programme. The sites are being selected as a basis for validating satellite-derived global land-cover distributions. The sample datasets are representative of a range of global land-cover types and, where possible, are located where there are ongoing field-based monitoring programmes.
- A good example of a regional/continental scale land-cover mapping study is the recently completed USFS/USGS US Forest Cover Map. This map was produced using the 1 km AVHRR dataset generated by Loveland (1992). A similar effort is being undertaken by the US Forest Service for Mexico with the help of in-country collaborators. An Interagency Multi-Resolution Land Cover Characterization (MRLC) project, implemented by the United States Geological Survey (USGS) on behalf of a number of federal agencies including the Environmental Protection Administration (EPA), is generating land-cover datasets for the conterminous US. These datasets include products from coarse and high spatial resolution satellite sensors.
- An example of land-use intensity mapping is a study involving interpretation of Landsat imagery performed by USGS for the United States Agency for International Development (USAID), covering several countries in Southern Africa.
- There are several international projects, for example: the Corinne Project of the ECE, which has generated land-cover information for Western Europe; the proposed Africover Project of the UN/FAO, which will provide high resolution satellite derived land-cover data for Africa; and the TREES Project of the ECE, which is providing comprehensive forest-cover mapping of the entire tropical belt.

Integrating Activity 1.3. Land-cover change mapping

This Integrating Activity will: (i) define critical land covers and geographic regions; (ii) develop datasets of land-cover change in each cover type for the past 20 years; (iii) develop datasets of land-use/cover change from tabular statistics for the past 100 years; and (iv) coordinate with IGBP-DIS High Resolution data and other relevant projects. While global land-cover stratification/classification can be achieved at the 1-2 km resolution, precise measurement of changes in land-cover conversion will require information of a much higher resolution. Thus, the activity emphasises high resolution remote sensing of land-cover conversion. It would provide comprehensive data on land-cover conversion over very large regions, building on existing pro-grammes through continuation of ongoing efforts coupled to new efforts in important regions not heretofore covered under existing activities. One emphasis should be on obtaining quantitative and geographically-referenced datasets on the dynamics of deforestation and reforestation (secondary growth).

The activity should begin with a careful definition of science requirements, key regions of study being targeted with the intent of making specific and direct contributions to global change research, national goals, or international policy. Next, it would be important to develop a well-designed data plan or acquisition strategy. Because it will not be possible to get global coverage from Landsat alone until the launch of Landsat 7 later in this decade, a multi-sensor acquisition model is the only feasible approach for global coverage. This involves the development of international cooperation with other satellite operators. Some of the important programmatic groundwork is being laid through the IGBP/CEOS High Resolution Data Exchange Project. Still, technical work must be done to develop an efficient acquisition scheme involving several sensors that differ in coverage, resolution, formats, repeat times, and other characte-ristics. With Landsat alone, coverage can only be obtained where there are ground stations. Acquiring data through purchase agreements with ground stations is difficult and time-consuming. A careful acquisition plan for high resolution data must be made based on scientific and technical priorities.

Forest monitoring using high resolution data such as that provided by Landsat or SPOT could provide wall-to-wall mapping for an entire region. An initial mapping effort would define where and how much land-cover change exists in a region; thereafter, the stratification of forest types and critical regions could be enhanced by the use of coarse resolution information from Activity 1.2 above.

Acquisition of Landsat imagery can be coordinated regularly every 3-5 years to obtain cloud-free coverage systematically throughout the regions of interest defined by the acquisition plan. The best way to achieve this is to rely heavily on the foreign ground stations. These geographically-referenced measurements can directly support the IPCC process, which is being established to make inventories at intervals of approximately five years. This accurate and precise deforestation data would be an important contribution to the IPCC methodology concerned with biotic carbon dioxide emissions. To ensure that a uniform, consistent, and mutually agreed-upon method is employed, it would be necessary to convene a series of international workshops under the auspices of the OECD methodology-development activities.

To obtain annual estimates of deforestation and land-use change, a very efficient stratified sampling scheme could be employed to define deforestation rates between the complete inventory/census years, spaced 3-5 years apart. The stratified sampling could be accomplished using the last complete inventory/census, since this dataset would map the locations of deforestation. The assumption is that deforestation would be spatially persistent over the 3-5 year interval until the next complete inventory. To conduct this data acquisition effort, it will be important to coordinate it with the development of empirical models mentioned in Focus 2. These models could have highly predictive capabilities in regions of persistent patterns and rates of land-cover conversion.

The complete-coverage analyses to be made every 3-5 years could only provide inventories of the various land-cover classes (e.g., deforested land, secondary growth); they would not provide annual land-cover transition sequences, such as the change from forest to pasture to secondary growth and back to pasture. To do this it will be necessary to anchor a series of test sites, each the size of a single Landsat or SPOT scene, in which annual acquisitions are made. Co-registered scenes could be compared to determine the various land cover transition probabilities.

These test sites would also be used for a field validation and accuracy assessment effort which would define and track the measurement variance and error. This component will need to determine accuracy with respect to: (a) variance due to positional accuracy (i.e., the mapping precision); and (b) variance associated with image interpretation.

There is great promise that remote sensing techniques can be applied globally, but more research is needed to develop the techniques and approaches employed by existing land-cover change monitoring efforts, particularly for new regions outside the tropics, seasonal forests in the tropics, savannas, and other land-cover types. The methodological issues include the development of classification techniques, objective boundary/class definitions, best means for change detection, registration and orbit navigation, and scene processing. The specific method employed may vary from region to region. It is necessary, therefore, to define appropriate methods for each region of interest.

The technical research and development should be linked to the programmatic infrastructure so a uniform method can be utilised in IPCC and FCCC activities. A workshop series developed through the OECD could be a useful starting point for defining a common methodological framework which could be integrated into the existing OECD/IPCC methodology.

The degradation of forests is becoming an important issue, yet more research needs to be done before it will be possible to incorporate this approach into remote sensing techniques. It is feasible that satellite data can be used to quantify the areas of forest which have been degraded for selective logging.

As biomass burning is an important cause of land-cover conversion and an important land-use practice, data should be acquired on the rate and area affected by biomass burning. Different methodological approaches have been developed in different vegetation systems as a function of the longevity of the burn scar features and their spatial scale. The use of active fires provides direct information on the timing and location of fire activity, but is an intermediate step in determining area burned. Both coarse and high resolution satellite data are used in the existing approaches to monitoring and calibrating burned area; a global satellite data acquisition strategy is needed to support this research.

The development of global fire and burned-area products is an important issue. The current regional approaches must be evaluated and refined in the context of developing a global monitoring system. It is likewise essential that an assessment of the accuracy of the areal estimates be provided for each technique.

The programme should develop direct links to, and integration with, international efforts with the following programmatic infrastructure: governmental global change (through IAI, APN, ENRICH); non-governmental global change (IGBP, START, HDP, WCRP); observational/monitoring programmes (GTOS), coordination and acquisition of data (IGBP-DIS, HDP-DIS, CEOS, LGSWOG), and assessments and in-country programmes (FAO/TFAP).

An effort focused on establishing in-country cooperation will be necessary. Such cooperation fulfils several ancillary but vital objectives: (a) it builds a process of national acceptance of the methods and results through active involvement; (b) it provides a mechanism for technology transfer and training for eventual implementation of national inventories based on remote sensing; (c) it facilitates logistical coordination of the field component; (d) it provides direct cooperation at various foreign ground stations; and (e) it enables cooperation with national and regional experts in the interpretation of imagery.

To develop in-country collaboration, the programme should be linked to the emerging network of governmental and non-governmental activities. At one level (non-governmental), the programme could target activities that would contribute to the START regional efforts, such as that in Southeast Asia through which several LUCC projects/programmes have already been mounted; data collection efforts; and case studies. At another level it could support and participate in the governmental activities running parallel to START, such as the Asia Pacific Network (for Southeast Asia), ENRICH (for Africa, Eastern Europe, and Central Asia), and Inter American Institute (for North and South America). These networks are likely to be a good connection to an international consortium of funding from the USA, EU, and Japan.

Another approach would be to couple historical reconstruction of land-cover conversion derived from tabular documents with remote sensing. Tabular data, national censuses, or historical documents in which data are reported geographically (e.g., by administrative district) could be mapped in a geographic information system. Remote sensing provides direct observations of land-cover change, while historical reconstruction generally relies on indirect estimation from changes in various human-use categories. Nonetheless, the coupling of these two approaches provides a way to "calibrate" the historical assessment, since the historical trend should overlap with remotely sensed data - both in magnitude and space - during the years for which both historical and remotely-sensed data exist.

This approach relies on the availability of historical documents such as revenue records, gazetteers, land assessments, or forestry reports. In most cases, records of land use or agricultural area are more readily available than records of vegetation and land cover directly. Thus, estimates of land-cover change are indirectly derived from data on changes in agricultural area. A baseline delineation of natural land cover is established, and these areas are reduced in proportion to the increase in agricultural area.

Changes in the area of cultivated land can be used to approximate land-cover conversion rates, since the most important form of land-cover conversion has historically been agricultural expansion (Richards 1990, Tucker and Richards 1983). This assumption is generally accurate, but it must be noted that in some instances the omission of logging and other non-agricultural causes of land-cover conversion could be significant. Certain areas in the tropics, such as Ivory Coast, Nigeria, Malaysia, and Thailand, have experienced large-scale losses of forest in this way (Lanly 1982, WRI 1990; 1994). This approach is necessarily limited in the absence of direct observations of land cover. For instance, sparse sampling in space and time can result in a variety of possible time series in a single dataset, which may result in different histories of carbon flux when the data is coupled to a numerical model (Houghton 1986). To reduce this type of data aliasing, sampling at a finer temporal resolution would be required.

Also, data from the same source may vary considerably from year to year due to changes in methodology or terminology. Time-series derived from later editions of the FAO Production Yearbooks, an important source of this kind of data for recent history, are different from the same time-series derived from earlier editions.

It must also be noted that historical reconstruction does not actually document land-cover transformations, such as closed forest to woodland, due to human intervention. Instead, they provide estimates of land-cover replacement by agriculture, or land-cover conversion. Moreover, land-cover conversion estimates obtained this way are based on net changes in the amount of agricultural land. Since they are based on net change only, it is not possible to know how much abandonment there is at any point in time. For analyses of net fluxes of carbon, for instance, this could be important, since a large amount of abandonment would result in lower net releases to the atmosphere.

Historical reconstructions use tabular data only. There is no inherent spatial organi-sation to the data. One way to develop digital maps of historical land-cover conversion is to use geographic information systems (GIS). The GIS approach permits accurate spatial representation of data on agricultural areas, which can then be merged with digital maps of land cover to estimate conversion rates by land-cover type. It also makes it possible to integrate a wide variety of other data, such as roads and other human-use features, hydrology, soils, and the like, and to link historical data to remote sensing data.

There are several existing programmes upon which to build a land-cover change data Integrating Activity. For example:

- The Commission of the European Communities TREES project is compiling a 1 km tropical forest dataset in an effort to map the global distribution of tropical evergreen and seasonal forests. This dataset is being made available as raw data and high-level products, such as GIS-based forest maps, in an information system.
- NASA is developing an acquisition plan for a global series of test sites using Landsat TM data. These data are to be used to calibrate global analyses from coarse resolution data such as AVHRR, and for development of site-specific models of ecological processes in places where detailed in situ measurements have been made in conjunction with the satellite acquisitions. In a related effort, NASA is also compiling the Landsat Global Change Catalogue, which is a worldwide catalogue of Landsat data acquired in and outside the tropics for global change research. The data are available to the global change community at the cost of reproduction.
- The High Resolution Data Exchange Project is a joint project of the Committee on Earth Observation Satellites (an international affiliation of space agencies) and IGBP. This project is aimed at testing the utility of multi-sensor data acquisition and a multi-agency international coordinated system of remote sensing observations. It is building a dataset containing several hundred SPOT, MOS, JERS-OPS, ERS-1, and IRS data at selected global change study sites around the world.
- Regional Activities have been initiated in recent years which could be coupled to the programme outlined here for in-country work. Within the IGBP System for Analysis, Research and Training (START), a number of regional activities focusing on the land-cover change question have begun. Most notable is the Southeast Asian regional activity which is directly linked to the EPA Pathfinder project in that region, as well as the aforementioned IGBP-LUCC and High Resolution Data Exchange projects. START/Southeast Asia has initiated a Land-Use and Land-Cover Change (LUCC) programme consisting of two components: (a) a complete region-wide analysis of deforestation trends in the region, and (b) specific case studies established in four participating countries: Thailand, Malaysia, Indonesia, and the Philippines.
- In particular reference to the question of biomass burning data, the IGBP-DIS 1 km AVHRR data product could be a useful starting point for developing biomass burning maps globally. In addition, the Biomass Burning Experiment (BIBEX) of the IGBP International Global Atmospheric Chemistry (IGAC) core project is directly relevant, as are various other programmes of the IGBP.

Integrating Activity 1.4. Land-use and land-use change mapping

As noted above, it is doubtful that a single land-use classification system, even if it is hierarchical, can serve the varied needs of the user community. This science/research plan calls for two meanings - biophysical manipulation and intent/purpose - either one of which requires very different kinds of data. The aim of this activity, therefore, should be identify the data needs for either meaning, including common measures, and direct the larger community to collect these data in systematic ways that permit their flexible use.

Biophysical manipulation will require information on the techno-managerial inputs and strategies for major kinds of land use. Some of these inputs or their attributes can be detected from satellite imagery, such as the frequency of biomass burning in swidden cultivation and pasture/grassland management, terracing, and paddy systems. Most of the inputs cannot be observed in this manner and will require case-study sampling. Such inputs include irrigation, fertiliser use, movement of livestock, pesticide use, and so forth.

Intent/purpose data links directly with the behaviour of the land manager, and save in some special cases, such as large-scale tree plantations or centre-pivot irrigation in which the spatial form can be matched rather uniformly with intent/purpose for known regions, these data must be obtained from ground-based techniques and sources. The basic data needed relate to management aims as noted in the section above on classification. Several efforts are underway to develop land-use classifications and maps for the world.

Integrating Activity 1.5. Developing socio-economic datasets

The human dimensions datasets have not been well defined by the social science global change research community. At the earliest possible opportunity, it will be necessary to define the research requirements for data. This process should involve a collaboration between the Human Dimensions Data and Information Systems Office (HDP-DIS) and the IGBP-DIS Office. A workshop following the open science meeting should be the venue to engage the research community to define specific datasets; the role of the open meeting would be to define the science questions and specify topical areas which will need supporting data. These will certainly include economic, political/institutional, demographic, and policy data. Some of the obvious data are population density, patterns and level of consumption, land tenure, functioning of the market, and the like.

It is important to recognise here, however, that the data will be required at different scales of resolution. Typically, economic data are collected at the level of the state or country, while population data are collected at sub-country levels. For land-use analysis, finer spatial resolution is preferable. Much political/institution and policy data are systematically collected, but must be drawn from individual case studies in the short run.

It is also likely that to develop LUCC datasets there will be a large amount of overlap and integration of social-science and physical-science datasets. For instance, analyses of forest regrowth offer new insights into the dynamics and implications of forest use. Patterns of regrowth and the conversion of secondary forest back to agriculture reflect important social processes. Regrowth may be the result of the abandonment of pastures and agricultural plots, or the result of deliberate resource management strategies. Simultaneous acquisition of the physical and social variables and measurements is necessary to understand this process. Another example is that of landscape fragmentation, where the degree of fragmentation is largely a function of the land-use patterns associated with different economic activities. The history of land occupation can also be an important factor.

One additional point must be made: satellite observations alone cannot explain the socio-economic and political factors that are the cause of land-cover change, nor can they identify the factors that influence regional trends or local dynamics. It is only possible to address these issues by also using demographic census data and other sources of relevant social science data. The social science variables should be merged spatially and temporally with the physical science data on land-cover change, along with other variables such as soil type, hydrography, kilometres of roads constructed, and distance to markets.

Finally, there should be serious recognition of the useful role of field-based data. The objective of field research would be to elicit information from land managers and other land-use decision makers in order to understand the individual-level decision processes that produce the land-use/cover changes.

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9. Integrating Activity 2: Scalar Dynamics

Introduction

Any analysis of land-use/cover change must come to grips with scale issues because the units of analysis and processes within them have scale-related properties, including threshold effects. An integration of Foci 1, 2, and 3 as proposed in this science/research plan requires that LUCC dynamics found at the micro-scale be linked to those at higher scales, ultimately in global models, and more generally that the units and processes found operative at the various scales of analysis be linked in a rigorous way that permits scalar coupling and decoupling. Integrative approaches among all these research foci will be required to ensure the robustness of these linkages.

Integrating Activity 2.1. Developing a scalar framework

This Integrating Activity seeks to design a hierarchical typology of broad clusters and/or specific driving forces of land-use/cover change according to the scales at which they typically operate. It aims to provide guidelines for the kinds of causes expected for the scale at which the question is posed or the analysis undertaken. Its analogue is the space/time matrices developed for the physical dimensions of environmental change (McDowell, Webb and Bartlein 1990; Allen and Hoekstra 1990) as well as some of the proximate sources of change in general (Clark 1987).

An estimate of the grain and extent of scales is essential to define particular pheno-mena. Representing scale in a space/time matrix often portrays the range of scales over which a phenomenon occurs (Clark 1985), but an alternate representation is to show average grain and average extent for the phenomenon (Holling 1992). For example, villages are made up of households, so village-level processes would range from household size (grain) to village size (extent). The representation of scale differs with the question: if gender roles were at issue, then the grain of the study would be finer than the household, but the extent could remain the same.

A key, therefore, is to develop a strategy of data development that allows the data to be aggregated on at least three different scales (real-world, empirical, and model; see Section 3, Scalar Dynamics). Various data should be organised and matched as closely as possible according to their spatial attributes. This matching may require the construction of artificial scales based on grid aggregations.

An objective method for the identification of scales must be developed in concert with Foci 1 and 2. Existing methods of scale identification (e.g., dominant frequencies revealed by Fourier analysis for temporal scales, Andres et al. 1994; discontinuities in fractal dimension for spatial scales, Krummel et al. 1987) should be extended and refined, and new methods explored (e.g., univariate clump analysis, Holling 1992). Such methods should be applied consistently to available datasets, first to fine resolution, remotely-sensed data, and then to socio-economic data from Focus 3 and case-study data from Focus 1.

Scalar discontinuities can also be identified by the failure of prediction and extra-polation when extended spatially or temporally. For example, deforestation in the Amazon basin could be predicted fairly accurately from 1978 to 1988 based on a simple Markov model, but these predictions became inaccurate when extended past 1988, because exogenous economic and political factors operating on different time scales began to define a new period (Skole, personal communication). If unpredictability and surprise characterise scale transitions, then measures of unpredictability or variance might be used to mark critical thresholds and to define limits to extrapolation (Turner et al. 1989).

A wealth of LUCC case studies at varying spatial and temporal scales have been undertaken. Similarly, a large set of models of land-cover dynamics and a smaller set of models of land-use and land-cover conversion have been developed. Systematic assessments of their data requirements and outcomes as they pertain to the issues of spatial and temporal dynamics have been lacking, however, and should be undertaken with the goal of deriving a trial space/time matrix for the human causes of LUCC. A typology of driving forces must be developed and applied to the case study and modelling literature. Three sets of scales should be addressed: those for real-world mechanisms (Focus 1), empirical measurements (Focus 2), and prognostic models (Focus 3).

Case studies of land use (Focus 1) should be multi-scale in a given locale (Turner et al., 1989), where possible, and nested within regions of particular attention (as in Focus 2). Thus linkages must be made from the household and high resolution (<1 km) to the region and from months to decades up and more. These linkages might be refined by examining the results of Foci 1, 2, and 3.

Integrating Activity 2.2. Developing rules for crossing and linking spatial scales

Simply analysing data and modelling at multiple scales is a way of addressing scales without crossing them; as such, cross-scale dynamics are treated as a black box. Simple aggregation strategies which deserve attention may be treated as a methodological (observational) issue only. An overarching aim of the LUCC enterprise is to couple qualitative models at the scale of case studies (from Focus 1) with regional thematic models (Focus 2) and to couple regional models of change with global models (Focus 3). This coupling and decoupling must adequately account for the processual dynamics of the forcing functions found at each scale. For example, global agricultural markets may operate as demand on a region's land use, but its path to land use may be filtered, augmented, or radically changed by regional resource institutions, politics, and other such factors. In turn, these regional factors cannot be situated independent of the global market. Getting the scalar dynamic right, therefore, is central to improving regional and global models. This observation can be extended to the sub-regional level as it applies to the case studies of Focus 1.

Simple notions of hierarchy theory imply that broad-scale driving forces effectively constrain smaller-scale, immediate variables which, in turn, affect higher hierarchical levels as an average. If systems are vertically coupled but in a loose manner (Pattee 1973), then it makes sense to model scales separately. But when different hierarchies are joined (as in the land-use/land-cover linkage), this sort of hierarchy may not apply. In addition, land-use systems are evolutionary even on short time scales, so that hierarchies are dynamic. Thus, constraining variables progressively in their weight and importance, even at a single spatial and temporal scale, may show their effect in discontinuous, non-linear ways. Uncovering the coupling mechanisms within hierarchies of systems and processes and describing their strength over time is essential.

Complementing these mechanisms, the Óconfidence limitsÓ in the structure and the outputs of various models should be described, thus defining the conditions under which extrapolation is and is not appropriate. Traditional statistical confidence limits place bounds on the certainty of estimation and prediction. Here we seek the level of that uncertainty as a function of the strength of the mechanisms that couple hierar-chical levels together. Making the evolution of thresholds and surprises truly endogenous to the model is a longer-term goal.

Spatial heterogeneity in both land use and land cover may affect the outcome of changes in driving forces in both the biophysical and social realm, but perhaps only at certain scales. Temporal heterogeneity in land use interacts with temporal hetero-geneity in biophysical driving forces (for example, seasons) in a non-linear fashion. Temporal heterogeneity in driving forces may be expected to affect the strategies of land users in their adaptation to and mitigation of risk and uncertainty. The use of variance rather than means in models may capture some of the role of system heterogeneity, but further methods should be developed, applied, and refined.

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Introductory Message from the Chairmen of the International Geosphere-Biosphere Programme (IGBP) and the Human Dimensions of Global Environmental Change Programme (HDP)

The Land-Use and Land-Cover Change Science/Research Plan is an important document for the global change research community and those interested in the subject for at least two reasons.

Firstly, the area of science is a vital one. Human alterations in land cover as a result of the use of land-based natural resources not only have local and regional impacts, but can also have important effects at the global level. For example, man-made changes in land use over the last 150 years have contributed about as much carbon dioxide to the atmosphere as has come from fossil fuel combustion. Many other examples are given in the report.

Secondly, this is the first time that the IGBP and HDP have mounted a combined initiative in which responsibility is equally shared between the two bodies. This is a significant achievement because the task is intrinsically large, and particularly considering the difficulties of developing productive partnerships, on an equal basis, between natural and social scientists. These two groups come from different traditions but, despite this, the joint IGBP/HDP Core Project/Research Programme Planning Committee has produced a well balanced report.

The Science/Research Plan presents the subject of land-use and land-cover change and ties it to the overarching themes of global change. It briefly outlines what is currently known and what knowledge will be necessary to address the problem in the context of the broad agendas of IGBP and HDP. Drawing on the expertise of specialists in various disciplines within the natural and social sciences, the authors have developed specific research questions and suggested methodologies for addressing them.

The next stage is putting this into practice, with the involvement of the widest scientific community possible. The LUCC Open Science meeting (Amsterdam, 29-31 January 1996) provides an important opportunity for discussions on how this will be achieved. Everyone interested in the development and implementation of the LUCC project/programme is strongly encouraged to come to the open meeting.

This consultation with a wide scientific community will provide input for the next stage, which will be the elaboration of an implementation plan that will specify in greater detail the activities and projects that will fulfil the mandate outlined in this document. Not only new projects but ongoing activities by individual scientists and other agencies will be potential partners for this path-breaking endeavour to address the interactions between natural and social processes in the use of one of manÕs crucial resources.

We would like to thank all those who have given freely of their time and intellect to bring the LUCC project to its present favourable position. They are too numerous to mention all of them by name, but we must give special acknowledgement to the group led by Billie Turner and David Skole who, with Steven Sanderson, GŸnther Fischer, Louise Fresco and Rik Leemans have edited and written much of this report, together with expert assistance from Jo‹o Morais at the IGBP Secretariat in Stockholm. To these and all the others who have been involved we are greatly indebted.

It only remains for us to wish the LUCC project/programme fair speed in the achievement of its ambitious agenda and express the hope that this first collaboration between our two programmes leads on to further joint ventures in the future.

Peter Liss	Martin Parry
Chairman,	Chairman,
Scientific Committee of the IGBP	Steering Committee of the HDP

Executive Summary

Land-use and land-cover change is significant to a range of themes and issues central to the study of global environmental change. The alterations it effects in the surface of the earth hold major implications for sustainable development and livelihood systems and also contribute to changes in the biogeochemical cycles of the earth, affecting the atmospheric levels of greenhouse and other trace gases. Understanding the nature of land-use/cover change and its impacts requires the joint efforts of natural and social science because of the expertise of each in certain key facets of the topic.

The global environmental change community has increasingly recognised the significance of land-use and land-cover change and the need for an interdisciplinary research approach to the subject. This recognition prompted the International Geosphere-Biosphere Programme (IGBP) and the Human Dimensions of Global Environmental Change Programme (HDP) to explore the possibility of a cooperative research project/programme with the general goal of improving our basic under-standing of the dynamics of Land-Use and Land-Cover Change (LUCC) globally, with a focus on improving our ability to model and project such change. The two pro-grammes commissioned a Core Project Planning Committee/Research Programme Planning Committee1) for Land-Use and Land-Cover Change (CPPC/RPPC LUCC) to create a science/research plan2) for a jointly sponsored LUCC core project/research programme.

This report constitutes the LUCC science/research plan as developed by the CPPC/RPPC in cooperation with a larger research community through several workshops and meetings. Section 1 introduces the subject and its linkages with other global change research programmes and projects. Section 2 outlines the CPPC/RPPC LUCC's mandate from the IGBP and HDP. Section 3 describes the LUCC problem and the main themes and issues involved in its study. Section 4 is an overview of the science/research plan, while Sections 5-7 detail the three main research foci, and Sections 8-9 are the two integrating activities of the plan.

The plan rests on the following observations:

1. That a truly international and interdisciplinary LUCC core project/research programme is possible 2. That a sufficiently large cadre of scientists and social scientists exists worldwide to undertake the effort now 3. That LUCC-related projects and programmes are emerging in various segments of the global change research community, many of them in anticipation, but independent, of an IGBP-HDP core project/research programme 4. That these various initiatives are, individually and in the aggregate, insufficient for the global nature of the problem, which requires the kind of integration and inter-disciplinary effort that an IGBP-HDP core project/research programme can provide. The plan is guided by five overarching questions, specifically: 1. How has land cover been changed by human use over the last 300 years? 2. What are the major human causes of land-use change in different geographical and historical contexts? 3. How will changes in land use affect land cover in the next 50-100 years? 4. How do immediate human and biophysical dynamics affect the sustainability of specific types of land uses? 5. How might changes in climate and global biogeochemistry affect both land use and land cover, and vice versa?

Because the study and analysis of research addressed by LUCC covers a new interdisciplinary area, and because it is recognised that considerable integration of LUCC research with that of other Core Projects will be necessary, these goals will only be met through close collaboration with other Core Projects.

The plan calls for a set of integrative research foci and activities linking the various components of the LUCC research community in an effort to improve understanding of: (i) the driving forces (exogenous variables) of land use as they operate through the land manager; (ii) the land-cover implications of land use; (iii) the spatial and temporal variability in land-use/cover dynamics; and (iv) regional and global models and projections of land-use/cover change.

These questions are addressed by three research foci:

Focus 1 Land-Use Dynamics, is a comparative case study approach aimed at improving our understanding of the variation in the nature-society dynamics of land management, thereby facilitating a sophisticated approach to regional and global modelling. It aims to identify and analyse a series of regional situations that represent the major clusters of LUCC dynamics worldwide, including the dynamic forces of these dynamics, thus permitting spatial and temporal fine-tuning of the overall modelling effort as well as providing the local, and, with Focus 2, regional understanding that is vital for climate impact and sustainability research.

Focus 2 Land-Cover Dynamics, involves regional assessments of land-cover change as determined from direct observation (e.g., satellite imagery and field studies) and models built from these observations. It seeks to provide spatial specificity in the land-cover outcomes associated with the management practices of particular land uses. In doing so, it links the underlying driving forces and land uses found in the case studies of Focus 1 to land-cover changes through management or proximate activities. It also extends and specifies the spatial coverage of particular LUCC dynamics, while providing models of change in this coverage.

Focus 3 Regional and Global Models, aims to improve upon existing models and build new ones that provide a basis for projecting land-use changes based on changes in the underlying causes or driving forces. These models will incorporate the regional and situational sensitivity provided from Foci 1 and 2 to generate more spatially explicit outcomes from regional and global models. Focus 3 will develop a model structure able to integrate a variety of approaches while strengthening agricultural sector models by including water, urban, biophysical, and other such linkages, and coupling these models to forest/timber and livestock sector models.

Two integrating activities cross-cut these three research foci:

Integrating Activity 1 Data and Classification, analyses data availability and quality and devises a classification structure suitable for the various needs of the three research foci. It also identifies, and, if needed, develops the major datasets and measures important for LUCC studies.

Integrating Activity 2 Scalar Dynamics, recognises that the different scales at which LUCC processes operate, and the different scales at which they are analysed, pose major impediments to developing a comprehensive understanding of LUCC. This activity seeks to identify the major rules and lessons that should guide LUCC efforts in this regard, thus improving the integration of the three foci.

The LUCC research activities will contribute to the following needs of the global environmental change communities:

1. Methodological advancement in the design and implementation of LUCC case studies and case study protocols, the means to interpolate and extrapolate from LUCC sample data across space and time scales, and the structure and functioning of integrated LUCC models 2. Analytical advancement in a suite of integrated LUCC models ranging from the household and farm to the globe 3. In cooperation with other projects and programmes, LUCC data development and format design 4. Empirically-derived inventories of geographically specific land-use/cover changes and analytically-derived projections thereof across specific time scales.

The understanding gained from the results of a LUCC project/programme will be of use to a wide range of researchers, policy planners, and other decision makers requiring improved means of projecting land-use/cover change in terms of its implications for (i) global environmental change, (ii) local-to-regional sustainability issues, and (iii) the assessment of responses to local and environmental change.

1. Introduction

The Problem

Land-use and land-cover change plays a pivotal role in global environmental change. It contributes significantly to earth-atmosphere interactions and biodiversity loss, is a major factor in sustainable development and human responses to global change, and is important to integrated modelling and assessment of environmental issues in general (Table 1). These diverse roles have been recognised in a large number of research publications and international conferences, symposia, and workshops devoted to the subject over the past few years (e.g., Bioscience 1994; Land Degradation and Rehabilitation [Thom 1994]; Meyer and Turner 1994), as well as the United Nations Agenda 21.

The international science research priorities on global environmental change require a firm understanding of land-use and land-cover change (Fig. 1). Natural science research on the states and flows of the biosphere, undertaken by the various core projects of the International Geosphere-Biosphere Programme (IGBP: established in 1986 by ICSU), addresses the effects of land-cover change (both conversion and modification) on ecological processes and systems and on earth-atmosphere dynamics. Land-cover change is driven largely by land uses. These uses and the techno-managerial practices that sustain them are a product of environmental factors, but also of complex political, social, and economic processes. How these latter factors and processes come together to drive land-use change is a central research problem of the Human Dimensions of Global Environmental Change Programme (HDP: established in 1990 by the ISSC). The two programmes share a concern for the systemic nature of the use-cover relationship, including the biophysical feedbacks on human activities and sustainability issues. Thus, land-use and land-cover change has the potential to integrate research on the natural and human dimensions of global environmental change, and the understanding gained from this integration contributes to other research and policy initiatives, such as those of the World Climate Research Programme (WCRP 1990) and the Intergovernmental Panel on Climate Change (IPCC 1990).

For all its importance to scientists and policy makers confronting the complexities of global environmental change, land-use and land-cover change is poorly understood. The long-term global character, extent, and rates of changes in land cover and some land uses are known in rough outline. Uncertainty and error remain relatively high (e.g., Meyer and Turner 1994), yet the advent of more precise and geographically referenced data on cover and use has created opportunities for improved analysis. Modelling the dynamics of land-use and land-cover change, however, has been hindered by the large variation in those dynamics across physical and social settings. Global aggregate assessments based on simple assumptions miss the target for large sections of the world, while local and regional assessments are too specific to be extrapolated to wider scales. Much work remains to be done to fill these increasingly critical gaps in understanding.

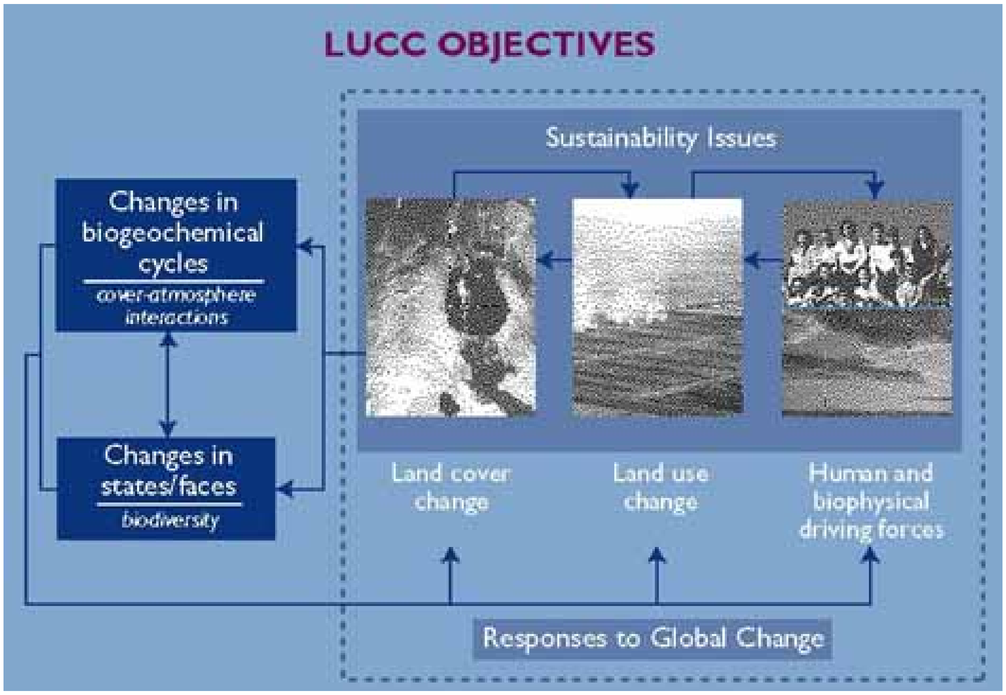

Figure 1. LUCC Objectives

The Science/Research Plan

Recognising the need to join the natural and social sciences to improve understanding of land-use and land-cover change, the IGBP and HDP in 1991 put together an ad hoc committee to explore the possibility of creating a joint core project/research programme on the subject. That committee recommended the creation of such a core project/research programme (Turner, Moss and Skole 1993) and identified the broad course of research that it might pursue. The IGBP and HDP agreed and in 1993 commissioned a formal Core Project Planning Committee/Research Programme Planning Committee to develop a LUCC (global land-use/cover change) science/ research plan for such a project/programme (Section 2). That plan, with revisions by the IGBP and HDP through a LUCC Interim Committee, is presented in this report.

LUCC is an interdisciplinary project/programme designed to improve understanding and projections of the dynamics of land-use and land-cover change as inputs to and consequences of global environmental change and as elements of sustainable development. This mandate requires new integrated global and regional models, informed by empirical assessments of the patterns of land-cover change and by comparative case studies of land-use processes, and is based on data and classification development. It also requires major improvement in understanding how processes of land-use and land-cover change vary across spatial and temporal scales and in incorporating that understanding into models. These five themes - integrated global and regional models, land-cover patterns, land-use processes, database and classification development, and cross-scale or scalar dynamics - form the research agenda of LUCC.

Table 1. Global Change Themes Requiring Land-Use and Land-Cover Change Information.

LAND COVER ATMOSPHERE INTERACTIONS

- Biogeochemistry
- Atmospheric chemistry
- Water and energy

BIODIVERSITY

- Ecosystem structure and function
- Species and genetic diversity
- Land-cover fragmentation

SUSTAINABILITY ISSUES

- Soil use and erosion rates
- Soil nutrient maintenance
- Water use
- Agro-ecological potential/ÓsupportÓ capacity
- Rural planning/environment and development
- National and international policy

RESPONSE TO GLOBAL CLIMATE CHANGE

- Land sensitivity to climate change
- Land use for mitigation

INTEGRATED MODELLING AND ASSESSMENT

Relationship to other IGBP-HDP Activities

Among the IGBP core projects (Fig. 2), LUCC links centrally to the activities of Global Change and Terrestrial Ecosystems (GCTE) and directly to various activities of the Biospheric Aspects of the Hydrological Cycle (BAHC), Land-Ocean Interactions in the Coastal Zone (LOICZ), International Global Atmospheric Chemistry (IGAC), Past Global Changes (PAGES) and Global Analysis, Interpretation and Modelling (GAIM). It links as well to the emerging agendas defined by various programmes for Global Change System for Analysis, Research and Training (START) programmes, of which Southeast Asia Regional Committee for START (SARCS) has made the most progress in incorporating LUCC issues. Within the HDP, LUCC links to programmes of study on Industrial Transformation and Energy Use, Demographic and Social Dimensions of Resource Use, Public Attitudes, Perceptions, Behaviour and Knowledge, Institutions, and Environmental Security and Sustainable Development. Beyond the IGBP - HDP, LUCC complements various activities of the World Climate Research Programme (WCRP - UNEP), the Intergovernmental Panel on Climate Change (IPCC - WMO and UNEP), Global Environmental Monitoring System (GEMS - UNEP), Global Terrestrial Observation System (GTOS - UNESCO and UNEP), and Man and the Biosphere (MAB - UNESCO). In addition, LUCC connects to the Food and Agricultural OrganizationÕs (UN FAO) land-use classification effort and the International Institute for Applied Systems AnalysisÕ (IIASA) new project on modelling land use and land cover.

The CPPC/RPPC and LUCC Development

A LUCC initiative was approved by the IGBP and HDP in February, 1993, and a Core Project Planning Committee (IGBP)/Research Programme Planning Committee (HDP) was selected to create a LUCC science/research plan that would integrate the natural and social sciences, following a mandate provided by its sponsoring organisations.

The CPPC/RPPC LUCC membership was:

GŸnther Fischer, Austria (HDP)
H. W. O. Okoth-Ogendo, Kenya (HDP)
Louise Fresco, The Netherlands (IGBP)
Martin Parry, UK (HDP)
Dean Graetz, Australia (IGBP)
Steven Sanderson, USA (HDP)
Teitaro Kitamura, Japan (HDP)
David Skole, USA (IGBP), co-chair
Rik Leemans, The Netherlands (IGBP)
B. L. Turner II, USA (HDP), chair

Luiz Martinelli, Brazil (IGBP)
Liu Yanhua, China (HDP)
Elena Milanova, Russia (IGBP)

The committee drew upon the assistance and advice of a wide range of experts. Immediately central to the execution of the science/research plan were: David Norse (UK), Senior Science Advisor for Focus 3, who took the original lead in the development of that focus; Lowell Pritchard (USA), Science Assistant for Focus 1; William B. Meyer (USA), Science Associate for LUCC; and Heather Henderson, Administrative Assistant for the CPPC/RPPC. In addition, the committee thanks Thomas Veldkamp (Netherlands), Ken Strzepek (USA) and Riga Suprapto (Indonesia) for their special contributions to the LUCC effort, and J. P. Hrabovszky (Australia/Hungary) for his valuable comments on the draft of the plan.

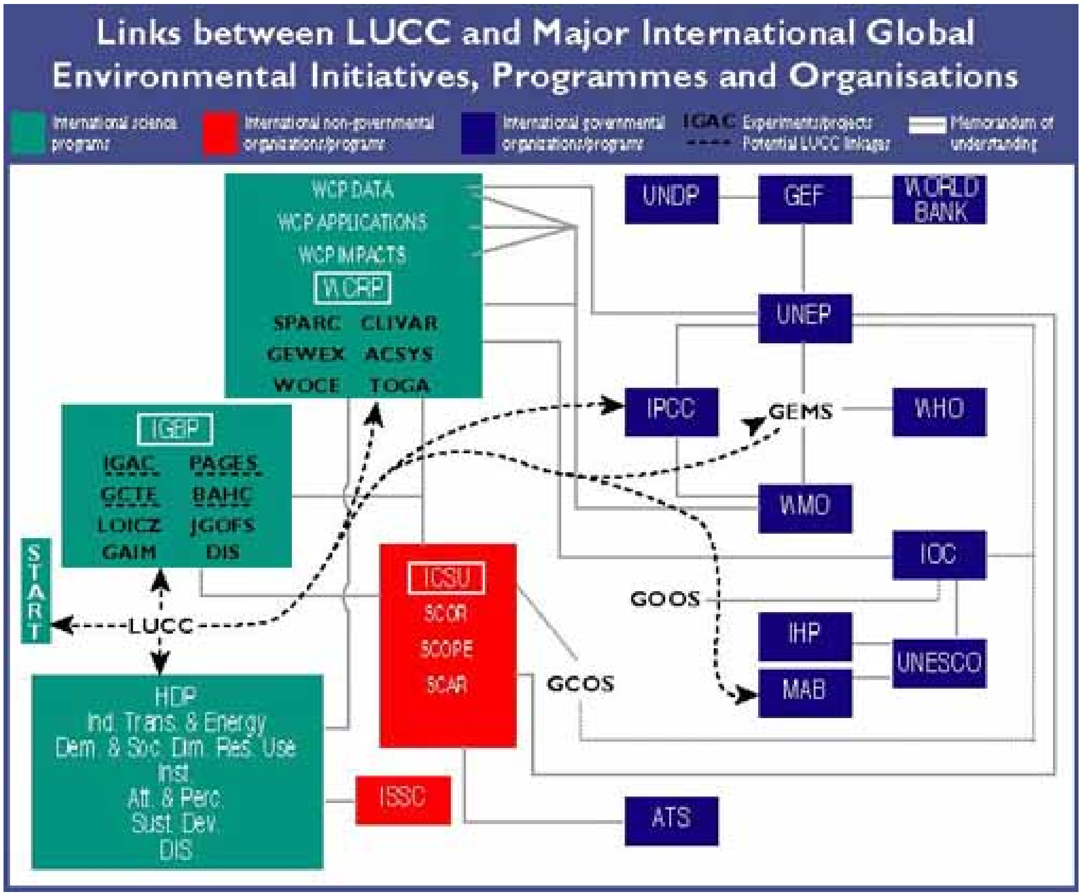

Figure 2. Links between LUCC and Major International Global Environmental Initiatives, Programmes and Organisations.

During the meetings of the CPPC/RPPC, the committee sought the advice of many experts from throughout the international community. These individuals are:

D. Bromley (USA)
K. Otsubo (Japan)
J. Bruinsma (Netherlands)
C. Padoch (USA)
H. Brookfield (Australia)
P. Pingali (Philippines)
G. Clarke (UK)
C. Poole (Spain)
J. Eddy (USA-CIESIN)
C. Rosenzweig (USA)
A. Gupta (India)
P. Richards (UK)
Y. Himiyama (Japan)
Y. Satoh (Japan)
J. Imbernon (France)
X. Singh (India)
J. Ingram (UK)
V. Stolbovoy (Russia)
I. Kayane (Japan)
R. Suprapto (Indonesia)
G. Leach (UK)
N. Swanberg (IGBP)
D. Major (USA-SSRC)

K. Strzepek (USA)
J-P. Malingreau (Belgium)
Y. Van Frausum (Belgium)
M. Mortimore (UK)
T. Veldkamp (Netherlands)
R. Moss (HDP-IGBP)
E. Wiegandt (HDP)
R. Munton (UK)
M. Williams (UK)
L. Olsson (Sweden)
A. Young (UK-FAO)

Finally, an Interim Committee on LUCC made revisions in the science/research plan as directed by the IGBP and HDP. This committee was composed of:

GŸnther Fischer, Austria (HDP)
Steven Sanderson, USA (HDP)
Rik Leemans, The Netherlands (IGBP)
Robert Scholes, RSA (IGBP)
Jerry Melillo, USA (IGBP)
David Skole, USA (IGBP), co-chair
Martin Parry, UK (HDP)
B. L. Turner II, USA (HDP), chair

For synopses and lists of participants for each CPPC/RPPC meeting relevant to various facets of the development of the science/research plan, please see Appendix 2.

Acronyms and Definitions

This report contains many references to various agencies, programmes, and projects whose titles have been abbreviated to acronyms. A list of these acronyms and their definitions is available in Appendix 4.

An interdisciplinary subject such as LUCC involves the use of terms that have different meanings and/or implications in different research fields. Throughout the text we provide definitions for key terms of this kind. The distinction between land use and land cover, for example, is detailed in Section 3. Land-cover change involves both conversion and modification; in this document, the use of the term land-cover change is intended to include both processes. The terms land-cover conversion and land-cover modification are used when referring to the individual processes. Similarly, as land use involves both the biophysical manipulation of the environment and the intent or purpose of the management processes, the term land use should be considered to refer to both processes, unless explicitly indicated otherwise. Driver(s), driving force(s) and forcing function(s) are used synonymously in this report to refer to what are known in some fields as exogenous variables. Finally, the report avoids the use of the terms prediction and cause, save in certain strictly defined cases.

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2. Scientific Mandate and Aims

Joint IGBP-HDP Core Project/Research Programme Planning Committee on Land-Use/Land-Cover Change

Introduction

Recognising the importance of land-cover change to environmental change and its human dimensions, and noting the main conclusions of the joint IGBP-HDP Working Group on Land-Use/Land-Cover Change, namely that:

- Understanding the past and future impacts of changes in land cover is central to the study of global environmental change and its human driving forces and impacts, including hydrology, the climate system, biogeochemical cycling, ecological complexity, land degradation and its impacts on agriculture and human settlement
- Land-cover modelling will require improved knowledge of land use, as it will be difficult to project future states of the land cover without knowledge of the factors that determine land use and drive land-use change
- The most likely determinants of land use are: demographic factors such as population size or density; technology; level of affluence; political structures; economic factors such as systems of exchange or ownership; and attitudes and values
- Additional basic research is required to understand how these factors interact to determine land use and drive land-cover change and how information about these factors could be used to project future patterns of land use, future rates of land-cover change, or future states of land cover
- Regionalisation and coordinated case studies are necessary for further investigation of changes in land use, their causes, and their implications for the functioning of the Earth system
- The knowledge gained through regionalisation and case studies will be crucial to developing regional and global land-use/cover-change models.

The International Geosphere-Biosphere Programme (IGBP) and the Human Dimensions of Global Environmental Change Programme (HDP) jointly establish a Core Project Planning Committee (CPPC)/Research Programme Planning Committee (RPPC) to set up a joint core project/research programme on Land-Use/Land-Cover Change.

Tasks

The CPPC is charged with drafting a detailed science/research plan for an IGBP-HDP project/programme on land-use/cover change, building on the framework of study outlined in the report of the joint working group. The science/research plan prepared by the CPPC will:

- Address the needs of the core projects and proposed core projects of the IGBP, in particular GCTE, IGAC, BAHC, and LOICZ
- Contribute to the projects and activities of the HDP, including Industrial Transformation and Energy Use, Demographic and Social Dimensions of Resource Use, Public Attitudes, Perceptions, Behaviour and Knowledge, Institutions, and Environmental Security and Sustainable Development
- Define the data needs of the project/programme and specify how these needs can be fulfilled in cooperation with the IGBP-DIS and HDP-DIS (Data and Information System).

As appropriate, the plan will also:

- Contribute to the definition of relevant START activities
- Make use of the outputs of PAGES
- Make use of the outputs of the HDP Data Programme.

Composition

The CPPC will be composed of 8-12 individuals with broad scientific backgrounds and will be international and multi-disciplinary in composition. The members of the CPPC will be appointed jointly by the Scientific Committee of the IGBP (SC-IGBP) and the Steering Committee of the HDP (SC-HDP).

Mode of Operation and Timetable

In preparing the detailed science/research plan, the CPPC will:

- Actively interact with the core projects/research programmes and activities of the IGBP and the HDP
- Hold an open scientific meeting to discuss and assess its detailed science/research plan.

The CPPC will complete its work in approximately one year. The IGBP and HDP contribute to funding the work of the CPPC.

At the conclusion of the work of the CPPC, and assuming approval of the proposed plan by the SC-IGBP and the SC-HDP, a Joint Scientific Steering Committee for the project/programme will be formed to carry out the science/research plan.

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Appendix 1: Science/Research Plan for Land-Use and Land Cover Change - Outline of Research Foci and Summary of Activities

Focus 1: Land-Use Dynamics - Comparative Case Study Analysis

Focus Activity 1.1 Developing a global sampling and study framework
Focus Activity 1.2 Identification, description, and qualitative modelling of the role of key driving forces of land-use maintenance and change
Focus Activity 1.3 Assessing the dynamics of change and stability in systems of land use
Focus Activity 1.4 Analysing land-cover consequences
Focus Activity 1.5 Theoretical work: model building and prediction

Focus 2: Land-Cover Dynamics - Direct Observation and Diagnostic Models

Focus Activity 2.1 Determining important land-cover changes and regions of consideration
Focus Activity 2.2 Direct measurement of regional and global land cover and land use
Focus Activity 2.3 Direct observations of land-cover change dynamics
Focus Activity 2.4 Analysing the spatial relations of land-cover change
Focus Activity 2.5 Observing the proximate causes of land-cover change
Focus Activity 2.6 Developing empirical diagnostic models

Focus 3: Regional and Global Models - Framework for Integrative Assessments

Focus Activity 3.1 Exploring existing regional and global models projecting land use and land cover
Focus Activity 3.2 Creating a new structure for modelling land-use and land-cover change
Focus Activity 3.3 Extending the horizontal linkages
Focus Activity 3.4 Refining the vertical linkages
Focus Activity 3.5 Introducing water into the land-use and land-cover change projections
Focus Activity 3.6 Model validation and sensitivity analysis

Integrating Activity 1: Data and Classification

Integrating Activity 1.1 Developing land-use and land-cover classification systems
Integrating Activity 1.2 Land-cover mapping
Integrating Activity 1.3 Land-cover conversion mapping
Integrating Activity 1.4 Developing socio-economic datasets

Integrating Activity 2: Scalar Dynamics

Integrating Activity 2.1 Developing a scalar framework
Integrating Activity 2.2 Developing rules for crossing and linking spatial scales

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Appendix 2: LUCC Meetings and Participants

1. CPPC/RPPC-LUCC, Barcelona, Spain, May 13-15, 1993

Host: HDP Secretariat

Synopsis: The first meeting of the CPPC/RPPC LUCC considered the IGBP-HDP mandate (Section 2) and developed an overarching conceptualisation of a LUCC programme consistent with that mandate. The initial formulation identified a case-study approach and an integrative-modelling approach for the LUCC objectives.

Participants:

G. Fischer
L. Fresco
D. Graetz
T. Kitamura
R. Leemans
L. Martinelli
E. Milanova
R. Moss
D. Norse
M. Parry
C. Poole
S. Sanderson
D. Skole
B.L. Turner
L. Yanhua

2. CPPC/RPPC-LUCC, New York, US, July 29-31, 1993

Host: Social Science Research Council

Synopsis: The committee and invited experts examined the strengths and weaknesses of integrated regional and global models, and the possibilities of linking them with detailed case studies. The group concluded that issues involved in the modelling and the linkages were sufficiently large that they required the development of a series of background papers, to be reviewed in a workshop by experts engaged in both modelling and case-study approaches.

Participants:

D. Bromley
J. Bruinsma
J. Eddy
G. Fischer
L. Fresco
D. Graetz
T. Kitamura
R. Leemans
D. Major
L. Martinelli
E. Milanova
D. Norse
H. Okoth-Ogendo
C. Padoch
M. Parry
L. Pritchard
C. Rosenzweig
S. Sanderson
D. Skole
B.L. Turner

3. LUCC Workshop, Woodstock, England, November 16-19, 1993

Host: Environmental Change Unit, University of Oxford

Synopsis: Some 25 experts on land-use/cover modelling and change from around the world were invited to join members of the CPPC/RPPC LUCC to explore and identify how integrative models could realistically be improved with regard to LUCC, and how the case-study community and the modelling community might merge their research efforts. In intensive break-out sessions, the participants worked on developing research foci and their required basic activities. The workshop resulted in the rudiments of Foci 1 and 3 and served to bring advocates of the case-study approach and the modelling approach closer together. The CPPC/RPPC LUCC set the goal of completing a full draft of a LUCC science/research plan to be reviewed at its next meeting.

Participants:

H. Brookfield
G. Clarke
G. Fischer
L. Fresco
D. Graetz
A. Gupta
J. Imbernon
J. Ingram
G. Leach
J.-P. Malingreau
M. Mortimore
R. Munton
D. Norse
H.W.O. Okoth-Ogendo
L. Olsson
M. Parry
P. Pingali
L. Pritchard
P. Richards
S. Sanderson
X. Singh
V. Stolbovoy
K. Strzepek
R. Suprapto
B.L. Turner
Y. Van Frausum
M. Williams
A. Young

4. CPPC/RPPC LUCC Mini-Workshop, Moriyama, Japan, June 16-18, 1994

Hosts: Centre for Global Environmental Research, National Institute for the Environment, Japan; Laboratory for Regional Planning, Kyoto University; City of Moriyama; IGBP-HDP National Committee, National Science Council, Japan

Synopsis: The committee and invited experts were asked to review the draft science/research plan and propose changes. Foci 1 and 3 were fine-tuned and a third focus (Focus 2) was added. This addition recognised that a major approach to understanding LUCC is through direct observation of land-cover change dynamics, primarily using remotely-sensed imagery, and that this approach is fully capable of developing empirical LUCC models of cover change. Focus 2, therefore, emerged as a complement to Focus 1 and 3, bridging the use dynamics of the case-study approach with the regional -global modelling approach. The CPPC/RPPC LUCC set as its next goal the completion of a further draft of the science/research plan, to be vetted by the committee and various emerging complementary activities. Completion date for the draft was set for October, after which the plan would be submitted to the IGBP-HDP in the late Fall of 1994.

Participants:

G. Fischer
Y. Himiyama
I. Kayane
T. Kitamura
R. Leemans
L. Martinelli
E. Milanova
K. Otsubo
M. Parry
L. Pritchard
S. Sanderson
Y. Satoh
D. Skole
R. Suprapto
N. Swanberg
B.L. Turner
T. Veldkamp
E. Wiegandt

5. Meeting on Land-Use and Land-Cover Change of the IGBP-HDP National Committee, National Science Council-Japan, Kyoto, Japan, June 19,

1994

Host: National Science Council, Japan

Synopsis: Members of the CPPC/RPPC LUCC discussed the issues involved in understanding land-use/cover change and how these issues relate to problems of interest to various Japanese efforts under consideration. In turn, the Japanese participants offered comments on the published LUCC-related materials to date (e.g., IGBP Report No. 24/HDP Report No. 5).

Participants:

M. Akiyama
M. Araragi
Y. Ashinaga
A. Bito
J. Chitose
G. Fischer
T. Fujii
M. Fukuhara
H. Harasawa
K. Hashimoto
H. Hirata
Y. Himiyama
S. Ikeda
K. Jitsu
R. Kada
Y. Kaida
H. Kaji
I. Kayane
M. Kimura
T. Kitamura
T. Kosaki
E. Milanova
K. Mizuno
Y. Murayama
M. Nakano
S. Nishioka
K. Otsubo
R. Pritchard
R. Suprapto
D. Skole
S. Sanderson
Y. Sato
I. Seko
K. Takeuchi
T. Totokoro
H. Tsutsui
B. Turner
S. Uchida
T. Usui
T. Veldkamp
M. Yamamoto
K. Yamazaki
K. Yano
M. Yazawa
M Yoshino
Y. Yui

6. BP Workshop on Land-Use and Land-Cover Change, Bangkok, Thailand, August 5-6, 1994

Host: Asian Institute of Technology

Synopsis: In a workshop held to discuss possible coordination between the IGBP/START Land- Use and Land-Cover Change Project in Southeast Asia and the proposed IGBP-LUCC core project/research programme, CPPC/RPPC LUCC members representing Foci 1, 2, and 3 presented an overview of the LUCC science/research plan, and were given a review of current research projects in Southeast Asia which related to LUCC research. It was agreed that START would cooperate with a future LUCC core project/research programme.

Participants:

J. Boonjawat
G. Fischer
B. Goh
Y. Honda

K. Kajiwara
S. Lertlum
S. Murai
M. Omakupt
T. Pijakarcham
W. Salas
S. Sanderson
R. Shibasaki
O. Siriratpiriya
D. Skole
R. Suprapto
M. Takagi
S. Vibulsresth

7. IGBP-DIS High Resolution Data Meeting, Paris, France, September 7-9, 1994

Host: CNES

Synopsis: Representatives of national space agencies and data providers met with representatives of IGBP-DIS and the CPPC/RPPC LUCC to discuss the establishment of policies and procedures for obtaining remotely-sensed high resolution data, essential for research described in Focus 2.

Participants:

P. Backlund
B. Bertolini
H.-J. Bolle
S. Gotoh
J.-P. Malingrea
Y. Muranaka
K. R. S. Murthi
T. Phulpin Y. Suga
I. Rasool
A. Ratier
W. Salas
D. Skole
W. Steffen
J. Townshend
M. Usui
A. van de Griend

8. Land Use and Land Cover Project, International Institute of Applied Systems Analysis, Laxenburg, Austria, October 24-25, 1994

Host: IIASA

Synopsis: CPPC/RPPC LUCC members discussed the IIASA project with its Steering Committee in terms of the kinds of understanding of land-use/cover change that have emerged from the CPPC/RPPC deliberations. Particularly emphasised were potential parallels and contributions of IIASA to regional and global LUCC models as informed by comparative case studies. The IIASA project focuses on mid- and high-latitude Eurasia, particularly Russia and China.

Participants:

G. Fischer
P. de J‡nosi
J. Jagger
T. Kitamura
V. Kotlyakov
M. Parry
C. Rosenzweig
W. Tims
B.L. Turner
L. Yanhua

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Appendix 3: IGBP Reports

*Reports marked with an * are no longer available.*

No. 12 The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP). The Initial Core Projects. (1990)

No. 13 Terrestrial Biosphere Perspective of the IGAC Project: Companion to the Dookie Report. Edited by P.A. Matson and D.S. Ojima. (1990)

No. 14 Coast Ocean Fluxes and Resources. Edited by P.M. Holligan. (1990)

No. 15 Global Change System for Analysis, Research and Training (START). Report of the Bellagio Meeting. Edited by J.A. Eddy, T.F. Malone, J.J. McCarthy and T. Rosswall. (1991)

No. 16 Report of the IGBP Regional Workshop for South America. (1991)

No. 17 Plant-Water Interactions in Large-Scale Hydrological Modelling. (1991)

No. 18.1 Recommendations of the Asian Workshop. Edited by R.R. Daniel. (1991)

No. 18.2* Proceedings of the Asian Workshop. Edited by R.R. Daniel and B. Babuji. (1992)

No. 19 * The PAGES Project: Proposed Implementation Plans for Research Activities. Edited by J.A. Eddy. (1992)

No. 20 * Improved Global Data for Land Applications: A Proposal for a New High Resolution Data Set. Report of the Land Cover working Group of IGBP-DIS. Edited by J.R.G. Townshend. (1992)

No. 21 Global Change and Terrestrial Ecosystems: The Operational Plan. Edited by W.L. Steffen, B.H. Walker, J.S.I. Ingram and G.W. Koch. (1992)

No. 22 Report from the START Regional Meeting for Southeast Asia. (1992)

No. 23 Joint Global Ocean Flux Study: Implementation Plan. Published jointly with SCOR. (1992)

No. 24 Relating Land Use and Global Land Cover Change. Edited by B.L. Turner II, R.H. Moss and D.L. Skole. Also HDP/Report No. 5. (1993)

No. 25 Land-Ocean Interactions in the Coastal Zone: Science Plan. Edited by P.M. Holligan and H. de Boois. (1993)

No. 26 Towards a Global Terrestrial Observing System (GTOS): detecting and monitoring change in terrestrial ecosystems. (Report of Fontainbleau Workshop). Edited by O.W. Heal, J.-C. Menaut and W.L. Steffen. Also UNESCO/MAB Digest. (1993)

No. 27 Biospherics Aspects of the Hydrological Cycle: The Operational Plan. (1993)

No. 28 IGBP In Action: Work Plan 1994 - 1998. (1994)

No. 29 Africa and Global Change. Report from a Meeting at Niamey, Niger, 23-27 November, 1992. (1994)

No. 30 IGBP Global Modelling and Data Activities 1994 - 1998. (1994)

No. 31 African Savannas and the Global Atmosphere: Research Agenda. Edited by C. Justice, R.J. Scholes and P.G.H. Frost. (1994)

No. 32 International Global Atmospheric Chemistry (IGAC) Project: The Operational Plan. (1994)

No. 33 Land-Ocean Interactions in the Coastal Zone: Implementation Plan. Edited by J.C. Pernetta and J.D. Milliman. (1995)

No. 34 BAHC-IGAC-GCTE Science Task Team: Report of First Meeting. (1995)

No. 35 Land-Use and Land-Cover Change (LUCC): Science/Research Plan. B.L. Turner II, D. Skole, S. Sanderson, G. Fischer, L. Fresco and R. Leemans. (1995)

No. 36 The IGBP Terrestrial Transects: Science Plan. Edited by G.W. Koch, R.J. Scholes, W.L. Steffen, P.M. Vitousek and B.H. Walker. (1995)

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Appendix 4: Acronyms and Abbreviations

AET Actual Evapotranspiration
AGE Applied General Equilibrium
AGNPS Agricultural Nonpoint Source Pollution Model
APN Asia-Pacific Network (START)
AVHRR Advanced Very High Resolution Radiometer
BAHC Biospheric Aspects of the Hydrological Cycle (IGBP)
BIBEX Biomass Burning Experiment (IGAC)
CEC Commission of the European Community
CENTURY *Not an acronym* **-** *simply indicative of the long time-scale of the model*
CEOS Committee on Earth Observations Satellites
CIESIN Consortium for International Earth Science Information Network (USA)
CPPC Core Project Planning Committee (IGBP)
CREAMS Chemicals, Runoff and Erosion from Agricultural Management Systems
DIS Data and Information System (IGBP)
ECE United Nations Economic Commission Europe (UN)
ENSO El Niño - Southern Oscillation
ENRICH European Network for Research in Global Change (CEC)
EPA Environmental Protection Administration
EPIC Erosion Productivity Impact Calculator
ERS-1 European Space Agency Remote Sensing Satellite
ESA European Space Agency
ESCAPE The Evaluation of Strategies to address Climate change by Adapting to and Preventing Emmissions
EU European Union
FAO Food and Agriculture Organization (UN)
FCCC Framework Convention on Climate Change
FLIPSIM Firm Level Income and Policy Simulator Model
FORENA Forests of Eastern North America
GAIM Global Analysis, Interpretation and Modelling (IGBP)
GCTE Global Change and Terrestrial Ecosystems (IGBP)
GEMS Global Environmental Monitoring System (UNEP)
GIS Geographic Information System
GLASOD Global Assessment of Soil Degradation (UNEP/ISRIC)
GRID Global Resource Information Database (UNEP)
GTOS Global Terrestrial Observation System
HDP Human Dimensions of Global Environmental Change Programme (ISSC)
HMSO Her Majesty's Stationary Office
HTFIP Humid Tropical Forest Inventory Project
IAI Inter-American Institute for Global Change Research (START)
IBSNAT International Benchmark Sites Network for Technology Transfer
ICSU International Council of Scientific Unions
IGAC International Global Atmospheric Chemistry Project (IGBP)
IGBP International Geosphere-Biosphere Programme (ICSU)
IIASA International Institute for Applied Systems Analysis
ILO International Labour Organisation (Geneva)
IMAGE Integrated Model to Assess the Greenhouse Effect
IMF International Monetary Fund (Washington, D.C.)
IPCC Intergovernmental Panel on Climate Change (WMO/UNEP)
IRS Indian Remote Sensing Satellite
ISRIC International Soil Reference and Information Centre
ISSC International Social Science Council
IUCN International Union for the Conservation of Nature
JERS-OPS Japanese Earth Resources Satellite - OPS Sensor
Landsat Land Remote-Sensing Satellite (USA)
LGSOWG Landsat Ground Station Operators Working Group
LOICZ Land-Ocean Interactions in the Coastal Zone (IGBP)
LUAM Land Use Allocation Model
LUCC Land-Use and Land-Cover Change (IGBP/HDP)
MAB Man and the Biosphere Program (UNESCO)
MOS Marine Observational Satellite (Japan)

MRLC Interagency Multi-Resolution Land Cover Characterization
MSS Multispectral Scanner System
NASA National Aeronautics and Space Administration (USA)
NOAA National Oceanic and Atmospheric Administration (USA)
NPP Net Primary Production
OECD Organization for Economic Cooperation and Development
OIES Office of Interdisciplinary Earth Studies
PAGES Past Global Changes (IGBP)
PAT Population, Affluence, and Technology
RPPC Research Programme Planning Committee (HDP)
SAVANNA *No acronym. A process-oriented model of pastoral ecosystems*
SARCS Southeast Asia Regional Committee for START
SARUM Systems Analysis Research Unit Model
SC-HDP Steering Committee of the HDP
SC-IGBP Scientific Committee of the IGBP
SOTER Global and National Soils and Terrain Digital Database
SPOT Système pour l'Observation de la Terre (France)
SSRC Social Science Research Council (US)
START Global Change System for Analysis, Research and Training
SWAT Soil and Water Assessment Tool
SWRRB Simulator for Water Resources in Rural Basins
TFAP Tropical Forest Action Plans
TM Thematic Mapper (satellite sensor)
TREES Tropical Ecosystem Environment Observation by Satellite
UCAR University Corporation for Atmospheric Research
UN United Nations
UNEP United Nations Environment Programme
UNESCO United Nations Educational, Scientific and Cultural Organization
UNFPA United Nations Population Fund
USAID United States Agency for International Development
USDA United States Department of Agriculture
USFS United States Forestry Service
USGS United States Geological Survey
WCIRP World Climate Impacts and Response Programme
WCMC World Conservation Monitoring Centre
WCRP World Climate Research Programme (ICSU/WMO/IOC)
WMO World Meteorological Organisation (UN)
WRI World Resources Institute

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